PASSIVE SOUND CONTROL IN SYMPHONY CONCERT HALL DESIGN

A TEHSIS
SUBMITTED TO THE DEPARTMENT OF
INTERIOR ARCHITECTURE AND
ENVIRONMENTAL DESIGN AND
INSTITUTE OF FINE ARTS OF BİLKENT UNIVERSITY
IN PARTIAL FULFILLMENT OF THE REQUIREMENTS
FOR THE DEGREE OF MASTER OF FINE ARTS

By
EBRU ŞAHİN
SEPTEMBER, 1995

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SEPTEMBER, 1995

I certify that I have read this thesis and that in my opinion it is fully adequate, in scope and quality as a thesis for the degree of Master of Fine Arts.

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I certify that I have read this thesis and that in my opinion it is fully adequate, in scope and quality as a thesis for the degree of Master of Fine Arts.

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ABSTRACT

PASSIVE SOUND CONTROL IN SYMPHONY CONCERT HALL DESIGN

Ebru Şahin

M.F.A. In Interior Architecture and Environmental Design

Supervisor: Assoc. Prof. Dr. Cengiz Yener

September, 1995

In this study, passive sound control in symphony concert hall was studied. Necessary criteria for concert halls were described and design of the enclosure for music is examined. An experimental study was done so as to make an evaluation of the present situation in one of the concert halls in Ankara.

Key Words: Symphony Concert Halls, Sound, Passive Sound Control, Acoustics

ÖZET

SENFONİ KONSER SALONLARINDA DOĞAL SES KONTROLÜ

Ebru Şahin

İç Mimarlık ve Çevre Tasarımı Bölümü

Yüksek Lisans

Tez Yöneticisi : Doç. Dr. Cengiz Yener

Eylül, 1995

Bu tezin amacı, senfoni konser salonlarında önemli olan kriterleri ortaya koyarak, konser salonu binalarının mimari tasarımlarında, istenilen akustik ortamı, edilgen ses konrolü ile elde etmenin yollarını anlatmaktır. Yapılan deneysel çalışmayla, bir konser salonundaki mevcut ses dağılımı incelenmiştir.

Anahtar Sözcükler : Senfoni Konser Salonu, Ses, Edılgen Ses Kontrolü, Akustik

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1. INTRODUCTION

For the design of an auditorium, there are factors such as, planning for good visual, thermal, audial, olfactory, tactile environments, suitable sightlines, appropriate seating layout, etc. When the problem is planning a concert hall, the most important property of the space will be its acoustics, which will be the determinant factor for the success of the design.

Music is a complex phenomenon and therefore it requires a proper hearing of this complex sound with all its pieces of arrangement and interpretation. When, a musical composition is performed in an enclosed space to a large number of audience, both the enclosed space and its audience affect the character of sound heard. Because of this interaction, in designing a volume for music, the main purpose is to provide all members of the audience the same quality of sound, and an acoustic environment suitable to the type of music being played. The contribution of a well designed, acoustically suitable environment can add a lot to the satisfaction of a musical performance.

For the last few years, it is a fact that there are certain changes and developments in the music world. With the help of technological improvements in mechanical and computerized systems, it is possible to provide the necessary sound reinforcement, and artificial acoustical environments, which will please every audience in a concert hall. But when this is not the case, and passive sound control is desired in the space, all effects of electronic equipment must be handled by the proper design of the enclosure to satisfy the listeners.

Today, halls are not only enclosures that serve a musical performance, but they are becoming a new type of space in which large audience must be seated. The shape, size, and structure, the way of enclosures being treated, the seating layout, and application of a style are the factors which form the space, and give different impressions to the concert halls. Furnishing the space with these factors, to achieve the required acoustical environment is the main and the most important concern for the full enjoyment of the performance in the space.

In this study, as the first step, information about the mechanism of hearing, and nature of musical sounds will be given. After describing the most important criteria for concert halls, the design considerations in a concert hall will be explained in detail. The evaluation of the present acoustical situation in a concert hall, with a case study, will be the experimental part of the thesis.

The subject will be investigated in both conceptual and experimental ways. The conceptual part of the thesis will cover the results of a literature survey, and the experimental part, a case study, to evaluate the existing conditions of a concert hall in Ankara. A glossary will be included in the appendix to give definitions related with the subject.

2. PERCEPTION OF MUSIC

Audible sound involves the ear. The vibrations of a sound wave sets the eardrum in motion. The nervous system responds to the movement of the eardrum. The way in which the ear change physical vibrations into perceived sounds makes psychologists, physiologists, physicists, and linguists pay attention to that phenomena, but many of the answers are still not being received.

2.1 PHYSIOLOGY OF HEARING

The ear consists of three main sections, the outer ear, the middle ear and the inner ear, or cochlea (Figure; 2.1.). The visible outer ear and the ear canal are the two main parts of the outer ear. Lawrence, in Acoustics and the Built Environment , explains that:

> The *pinna* is the name given to the broad upper part of the outer ear and it is important for people to localize sound direction, particularly in the central plane, which is an imaginary vertical plane through the head , normal to the connecting line between the ears and equidistant from them. If a sound source is in the horizontal plane the sound received by the two ears will differ slightly in phase and intensity and this can be interpreted by the brain to determine its location (9).

The sound waves pass along the canal to the eardrum, or *tympanic membrane*, and set it into vibration. In the middle ear there are the eardrum, three small bones (known as hammer, anvil, and stirrup) situated in an air-filled cavity , and the entrance to the *Eustachian tube*. The sound induced vibrations of the eardrum are transmitted by these three bones to the *oval window* of the *cochlea.* As the atmospheric pressure is equalized on both sides of the eardrum, the eardrum can only respond to very small changes caused by the passage of the sound wave.

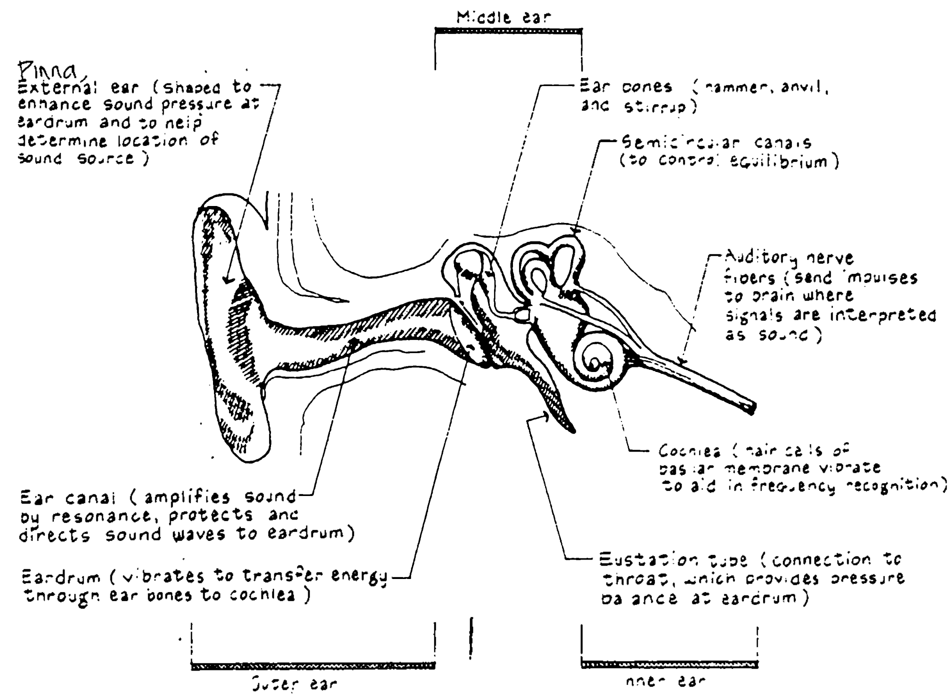


Figure 2.1. : A simplified section of ear through the mechanism of hearing (Egan 25).

The most important part of the hearing system is the inner ear, or the *cochlea.* It has a cavity coiled in a flat spiral of two and one-half turns. Lawrence states that:

> This cavity is partly divided into an upper and lower gallery by a bony structure and division is completed by the flexible *basilar membrane.* A second membrane, *Reissner's membrane* also divides the cochlea cavity above the basilar membrane. The cavities are filled with fluid. The action of the vibrating bones on the oval window causes the fluids on the cochlea

to vibrate, moving the cochlea partitions with them, as there is not sufficient area in the helicotrema opening to allow free movement of the fluid through it. The pressure is relieved by movement of the *round window* membrane (Acoustics 11).

The frequency of sound determines the location of the maximum displacement of the basilar membrane, and the sensitivity of ear (Figure; 2.2.). For example, low frequency sounds cause the maximum displacement to occur near the end, and higher frequency sounds cause the maximum displacement to occur near the bones and they cause little movement of the membrane further along. The ear is more sensitive to the high frequency sounds than the low frequency ones (Lawrence, Acoustics 11).

Some of the very complex structures are supported by the basilar membrane, including the nerve endings of the hearing organ. The *hair cells,* as hair-like projections project from their upper ends, are the actual sensory cells which are supported by the basilar membrane. "As the cochlea partition is displaced vertically by the sound-induced motion of the fluid, the tectorial membrane is displaced sideways, causing the hair cells to bend", says Lawrence in Acoustics and the built Environment and adds "it is thought that there are complex interaction stimuli between the cells and this enables the number, location and rate of stimulation of the nerve fibers of the two ears to be interpreted by the brain in terms of frequency, intensity, and location of the sound " (12).

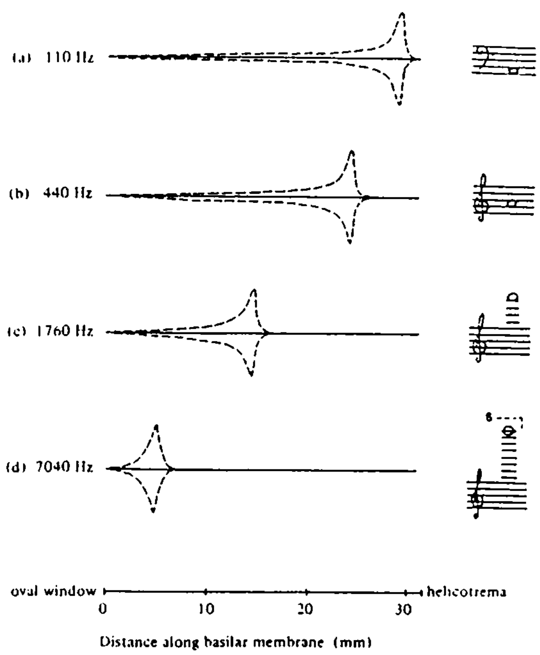


Figure 2.2. : Amplitude envelope of basilar membrane vibrations when hearing a pure tone of frequency (a) 110 Hz; (b) 440 Hz; (c) 1760 Hz; (d) 7040 Hz. The vertical scale is grossly exaggerated. The relationship between distance along basilar membrane and frequency of maximum response was derived from Bekesy (1960), p.440 (Campell 52).

For a normal young person, the human audio frequency range is commonly taken to cover the range between 20 and 20 000 Hertz . As people age they frequently lose their high frequency hearing acuity, thus their audio frequency range is reduced. The audio intensity range is from about 0 dB to 120 dB. The minimum level of sound that can be heard under ideal conditions is called the *threshold of hearing* , and the upper level is called the *threshold of pain*. However people do not perceive sound of all frequencies equally well; people are most sensitive to sound around 3 000 Hz and least sensitive towards the extremes of the audio range (Lawrence, Acoustics 13).

2.2 NATURE OF MUSIC SOUNDS

In order to predict and control the behavior of music in an enclosed space it is necessary to know the physical properties of music.

Sound is created by materials that vibrate. The molecules of the air surrounding the strings or membranes are set into motion by their vibrating surfaces. These moving air molecules push others around and produce an outward moving wave which has approximately a speed of 343 m / sec (Figure; 2.3.).

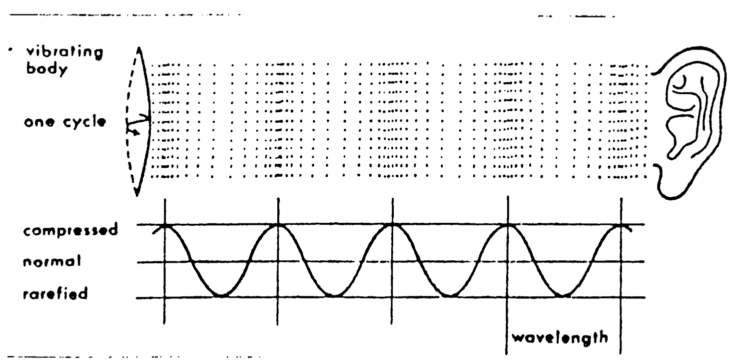


Figure 2.3. : The increase and decrease of pressure along the path between source and listener (Moore 2).

All vibrations are not alike. A long string or a long pipe or a large drum has slow vibrations and produces low frequency sound. If the dimensions of a string or a pipe are made shorter the vibrations will be more rapid and then produce a sound having high frequency. The intensity of a motion also differ the vibrations from each other. An instrument (a string or a membrane or a pipe) which radiates several sounds following each other, has capacity to vibrate in many different ways. Because of that, musical sounds have different properties to make listeners identify them (Beranek, Music 13-14).

Music is sound or combination of sounds that changes continuously or discontinuously with time. Musical sounds have four properties, namely (1) pitch, (2) loudness, (3) timbre or quality, (4) duration. The frequency of vibration of the source determines the pitch of a note. Loudness is determined by the intensity of the vibration of the source. The quality, or timbre is the property which characterizes notes of the same pitch when sounded by different instruments. The duration is the length of time that a tone persists or lasts in the musical composition.

Pitch is basically dependent upon the frequency of the sound source. Olson (29) describes pitch as "... a sensory characteristic arising out of frequency which may assign to a tone a position in a musical scale." Each pitch has special notation in music and its own frequency in the sound spectrum (Figure; 2.4.). The lower limit of pitch is the lowest frequency which gives a sensation of tone and the upper limit is the highest frequency which can be heard. The upper limit of pitch differ from individual to individual and decreases by the increase in age.

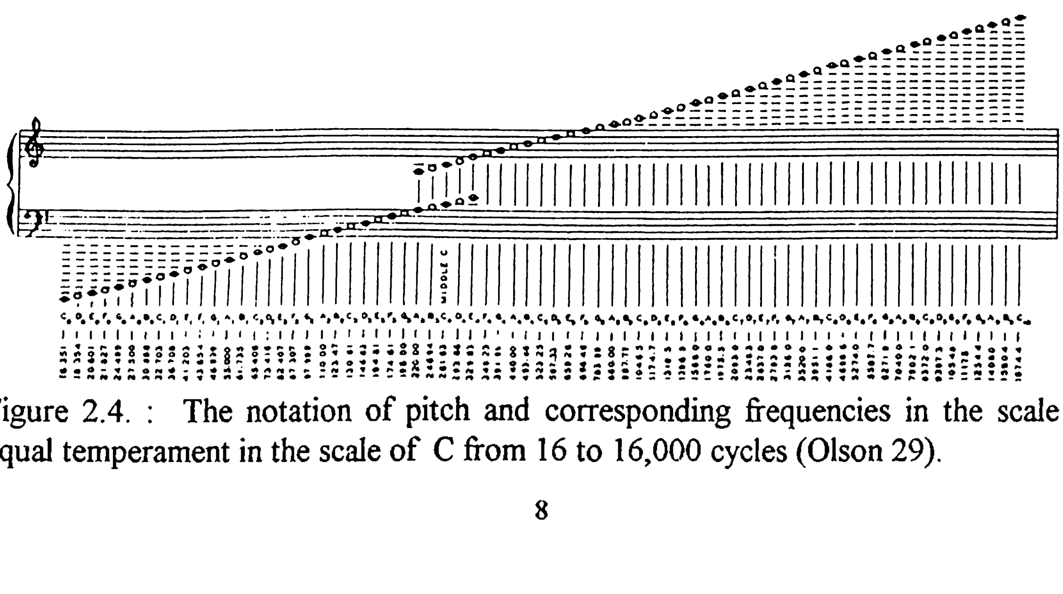


Figure 2.4. : The notation of pitch and corresponding frequencies in the scale of equal temperament in the scale of C from 16 to 16,000 cycles (Olson 29).

Loudness of a musical sound depends on the intensity of the sound source. Loudness and the variation of it are strong tools in achieving an exciting performance.

The frequency spectrum determines the sound quality or timbre of different musical instruments. Timbre is the most important basic characteristic of all music. It is the quality which enables the listener to recognize the kind of musical instrument which produces the tone. Moore (14) states that "A note produced by a musical instrument, however 'pure' it may seem to the ear is made up of a number of frequencies. It will have what is called a fundamental tone (by which we recognize its pitch) and a number of harmonics and overtones." Musical instruments and the voice produce fundamental frequencies and overtones of fundamental frequencies. Olson expresses the importance of these frequencies as "If musical instruments produce the fundamental without overtones, each instrument would produce a pure sine wave and would, therefore, be the same as the output of all other instruments except for the possibility of a difference in frequency and intensity" (37).

The fundamental frequency (first harmonic) is the lowest frequency component in a complex sound wave and determines the pitch of the sound. The higher frequencies are simple multiples of the fundamental frequency and are known as the second, third harmonic etc. These harmonics, which affect the musical quality, or distinguish the timbre of the instrument, are normally weaker than the fundamental frequency. "Because the harmonics are multiples of the fundamental frequency", says Moore, "their wavelengths will be simple subdivisions of the fundamental wavelength, so that the harmonics will appear as minor but regular disturbances of the original simple curve" (14) (Figure; 2.5.).

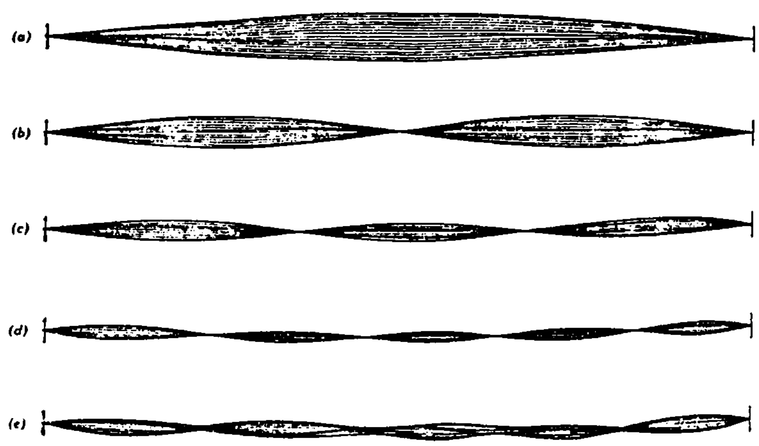


Figure 2.5. : Vibration of string: (a) at its fundamental frequency or first harmonic; (b) at its second harmonic; (c) at its third harmonic; (d) at its fifth harmonic; and (e) in resultant harmonic (Beranek, Music 15).

On the other hand some instruments do not produce simple harmonics having frequencies which are multiples of the fundamental frequency. Drums and cymbals can be given as examples to that group of instruments. Combinations of notes, produced by different instruments in the whole orchestra, will therefore present an even more complex frequency structure but, because of their tonal relationship the performance will keep the musical or harmonious character (Moore 14).

The low frequency music sounds have also large wavelengths which can usually bend round objects. At high frequencies the wavelengths of the sound are smaller than the object, obstacle dimensions within the enclosure, that allows the sound wave to be reflected from the surfaces in the space.

Music only begins when one tone is related to another. The importance is not upon one note, but upon the connection between that note and others have followed and preceded to form the composition to be appreciated and received as a musical sound. Moore discusses that:

> Combinations of notes... present an even more complex frequency structure but, because of their tonal relationship retain a musical or harmonious character. The tonal sound of an orchestra can thus be seen as an extremely complex combination of frequencies, especially when one takes into account the fact that some instruments, such as drums and cymbals, do not produce simple harmonics (14).

According to the conditions of music being performed, the sounds are produced at a rate of from 15 to 20 sounds per second. These sounds have duration of from 1 second to 2 second or more (Lawrence, Acoustics 42). Also Lawrence adds that:

> When a sound is produced from an instrument, it will have an *onset* time, a *steady state* period and a *decay;* during the initial onset of the sound, the fundamental and then the various harmonics become established, and considerable variations in instantaneous spectra may occur: these variations are called *transients.* There is evidence to suggest that an ability to hear these initial transients of a sound enables a listener to distinguish one instrument from another (86).

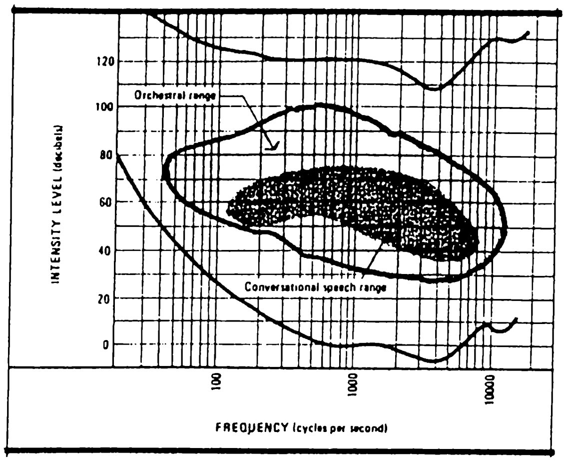


Figure 2.6. : Frequency range for conversational speech and for symphonic music (Flynn, Segil, and Steffy 74).

The audible power obtained from musical instruments, including the singing voice also, is usually greater than the power obtained from speaking (Figure 2.6.). As the sound pressure level of music in an enclosed space is higher than the average pressure level of speech, people have less difficulty in hearing music than in hearing speech.

Lowery adds "that music is not a physical but a mental phenomenon and that therefore *musical acoustics* involves psychological as well as physical laws is something that has only been recently recognized" (10).

2.3 BEHAVIOR OF MUSICAL SOUND IN AN ENCLOSURE

When a musical sound is produced in a room, sound waves will propagate away from the source until they meet one of the boundaries of the room. Usually some of the sound energy is reflected back into the space, some is absorbed by the surface met, and some will be transmitted through the boundary. Because of these conditions, the build up and decay of the sound in the space is highly affected by the surface characteristics. The shape, dimensions, and construction of these boundaries are the main factors constitute the acoustics of the room and behavior of sound in it. With the design of such boundaries, different acoustical events can be experienced in the concert hall during the performance which are necessary for the appreciation of music in the space (Figure 2.7).

The sound field around a sound source in an enclosed space has two components i.e. the direct field and the reverberant field. The very close region of the source is the near field. For the near field Ginn suggests "In this region the particle velocity is not necessarily in the direction of propagation of the sound wave. Furthermore, the sound pressure may vary considerably with position and the sound intensity is not simply related to the mean square pressure" (27).

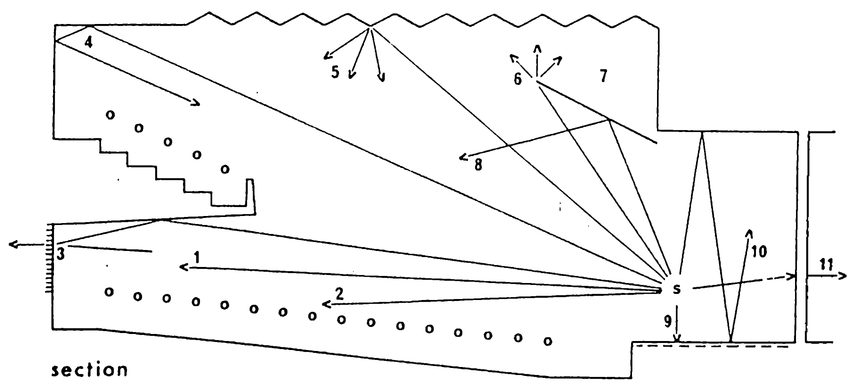


Figure 2.7. : Illustration of different acoustical events which may occur depending on the design of the room boundaries (Moore 140).
(1) attenuation due to distance
(2) audience absorption of direct sound
(3) surface absorption of direct and reflected sound
(4) reflection from re-entrant angle
(5) dispersion at modeled surface
(6) edge diffraction
(7) sound shadow
(8) primary reflection
(9) absorption of sound by the stage floor
(10) standing waves
(11) sound transmission

The extent of the near field is the far field in which the sound pressure level decreases 6 dB each time the distance between the source and the receiver is doubled. If the source is in an enclosed space , then the reflections of the sound waves from the boundaries of the room creates a reverberant field. This reverberant field is highly important in achieving the necessary sound intensity levels for the musical performances as it reinforces the unsatisfactory direct sound intensity levels far from the sound source.

3. ACOUSTIC CRITERIA FOR CONCERT HALLS

Music and acoustics are two disciplines that developed independent of each other, and have different explanations to describe their concepts. Some of the words are taken from dictionaries and given new meanings in these two disciplines. But as the interests and purposes of musicians and acousticians are different, the same words used by both sometimes describe different meanings although they sound the same.

In acoustics for concert halls, there are words developed to express the feelings, observations of the space in terms of subjective judgments (Table 3.1.). In addition to that there are objective criteria agreed upon by scientists to explain these subjective judgments in controlled ways.

3.1 SUBJECTIVE CRITERIA FOR CONCERT HALLS

Design of rooms for music has many difficulties to be handled by the designer as the frequency range of sound to be dealed is wider. Also the function of the room, and expectations from it are not only to have intelligibility, but also to provide good performance quality and a true production of sound. Several criteria are set on the basic of average subjective judgments for rooms where live music is played.

QUALITY		ANTITHESIS	
Noun form	**Adjectival Form**	**Noun Form**	**Adjectival form**
intimacy, presence	intimate	lack of intimacy lack of presence	non-intimate
liveness fullness of tone reverberation resonance	live reverberant resonant	dryness deadness lack of reverberation dryness	dry dead unreverberant dry
warmth	warm	lack of bass	brittle
loudness of the direct sound	loud direct sound	faintness weakness...	faint weak
loudness of the reverberant sound	loud...	faintness.. weakness...	faint weak
definition, clarity	clear	poor definition	muddy
brilliance	brilliant	dullness	dull
diffusion	diffuse	poor diffusion	non-diffuse
balance	balanced	imbalance	unbalanced
blend	blended	poor blend	unblended
ensemble		poor ensemble	
response, attack	responsive	poor attack	unresponsive
texture		poor texture	
no echo	echo free unechoic	echo	with echo echoic
quiet	quiet	noise	noisy
dynamic range		narrow dynamic range	
no distortion	undistorted	distortion	distorted
uniformity	uniform	non-uniformity	non-uniform

Table 3.1 Vocabulary of subjective attributes of musical-acoustic quality (Beranek, Music 64).

1) Intimacy or presence : The feeling of being enclosed in a space, with the sound field enveloping the listener, is important while designing the space for music. For an audience to sense the space in which he is sitting, sound must be reflected from many surfaces to the audience. The listener's impression of the size of the hall is determined by the initial time delay. Initial time delay gap is the time difference between the sound that arrives directly to the ear and the first reflection which arrives from walls or ceiling. Halls with intimacy or presence have sound reflecting surfaces which help the room have small initial time delay gap. For a hall to be intimate, the direct sound must not be too faint relative to the reverberant sound. Generally small halls have better intimacy characteristics (Beranek, Music 63).

2) Liveness : Reverberation time determines the liveness of a room. A room having too much sound absorbing materials is called dead as it reflects little sound back to the audience. A hall is said to be live when its interior surfaces are sound reflective and liveness of the room is directly related with the reverberation time of the space.

3) Warmth : Beranek, in Music, Acoustics, and Architecture, says " Warmth in music is defined as liveness of bass, or fullness of bass tone relative to that of mid frequency tone"(65). That is the case when the reverberation time for the low frequencies (250 Hz and below) is rather longer than the reverberation time for middle frequencies (500 Hz -1 kHZ).

Warmth appears to be equally important as liveness in its effect on the quality of a concert hall. Leopold Stokowski (cited in Beranek, Music) says "... the most serious acoustical problem in modern concert hall is the lack of bass. It requires more energy by the players to produce good low frequency sound in a concert hall... "(433).

A sound is *brittle* when the reverberation time at low frequencies is shorter and a sound is *boomy* when the reverberation time at low frequencies is longer. Boomy sound is achieved sometimes in large concert halls if high frequency sound is absorbed effectively by the wall or ceiling surfaces. Usually thin wood applications having an air space behind are the reasons for the deficiency of bass as the low frequency part of the sound is absorbed by these applications.

4) Loudness : The loudness of music in the concert hall is the component of direct and reverberant sound. In small halls, the direct sound of orchestra has adequate loudness for the back rows of the auditorium. But in large rooms, usually this is not the case especially when the seats are not raked adequately toward the end of the hall.

For good listening conditions, the music performed by the musicians must neither be too loud nor too weak. If the direct sound is too weak it may be masked by the background noise, or by the reverberant sound and that may cause the loss of clarity. Also too loud sound may cause uncomfortable listening conditions. The distance from the performing area to the listener, the nature of sound reflecting surfaces, and the size of the orchestra are some factors affecting the loudness of direct sound.

When the reverberant sound is considered for loudness, two things must be handled: One is the reverberation time of the hall with occupants and orchestra, the other is the intensity of sound that reaches the audience after reflections.

5) Definition or Clarity : When the sound is clear and distinct in the space, a hall is said to have definition. This criterion ables listeners to differentiate various instruments in the orchestra and different musical sounds from each other.

Poor definition gives music a blurred quality. Interior sound reflecting surfaces must be designed properly to have a high degree of definition. Intimacy, reverberation time, the distance of the listener from the performing area, and the volume of the hall are important features in determining the degree of definition.

6) Brilliance : Brilliance is the property of sound being bright, clear, ringing, and rich in harmonics. Sound energy at high frequencies and their decay in the hall are the factors affecting the brilliance of sound in the space. Other factors affecting are the initial time delay gap, the ratio of reverberation times at high frequencies to those at mid frequencies, and distance of listeners from the stage.

7) Diffusion : Diffusion is highly related to the spatial distribution of reverberant sound. Diffusion is best when the sound come to the audience's ear equally in every direction. Introduction of irregular interior surfaces in the ceiling, niches on walls, or balcony faces help orchestral sound to be diffused in the hall. Smooth side walls and ceiling make diffusion lost in a hall when they carry the music from the stage to the

listener without scattering the sound waves. Rather than these irregularities a more important contribution to the diffusion is the long reverberation time. If the room is not reverberant enough the sound wave will not be able to travel around the room, and because of that loses its chance to arrive at listener's ear from all direction.

It is stated that, poor diffusion may result when the stagehouse over the orchestra is reverberant but the rest of the hall dead. This kind reverberation, or design of stage can be beneficial to the music, but not satisfactory for the audience placed in the concert hall (Beranek 67).

8) Balance : "Good balance in the hall requires the balance between the sections of the orchestra, and the balance between orchestra and instrumental soloists" (Beranek, Music 67). To give good balance to the hall both acoustics and musical properties are important. After the suitable placement of instruments in the orchestra, stage enclosure must be designed properly for width, depth, and height with good diffusion characteristics to provide good balance.

9) Blend : It is the harmonious mixing of sounds from various instruments in the orchestra. It depends on the layout of the orchestra, design of stage ceiling and on the design of the surfaces introduced to the stage enclosure to mix the sound before it reaches to the audience.

10) Ensemble : It is the musicians ability to play in unity, and ease of hearing among performers. Beranek argues "Ensemble is partly a matter of the skill of the conductor

and the performers and partly a matter of the design of the stage enclosure or the reflecting surfaces at the sides and above the stage" (Music 447).

Good ensemble is highly related to how well the orchestra members could hear each other during the performance, and to the sound that is heard from the hall itself. Design of the stage enclosure and sound reflecting surfaces at the sides and above are important points which carry sound among performers.

11) Immediacy of response : This criterion is the hall's ability to give the musicians the feeling of immediate response when a note is being played. If the first reflections from the boundaries of the stage arrive back to the musician's ear after a long time he may perceive it as an echo. Because of that, the design of stage with properly designed reflecting surfaces is important for musicians to achieve immediacy of response for a comfortable and correct performance. Also it is important for performers not to achieve reflected sound from the audience area as an echo.

Good immediacy of response depends on the reverberation time, the initial time delay gap, freedom from echo, and the diffusion of sound. Reflections only from the nearby surfaces cause the performer feel acoustics of the stage different than it is (Beranek, Music 69).

12) Texture : Texture is the impression created in the mind of listener by the sequential arrival of reflections after the direct sound. Some halls have uniform initial time delay gaps between first, second, and third reflections, while others have not.

This pattern of reflections with initial time delay gaps forms a texture which is perceived by the listener.

13) Dynamic range : It is the range of sound levels over which music is heard. It extends from the faintest level (noise of the audience) to the loudest level produced by the performers. The highest level of the music is determined by the sound power of the orchestra and acoustical characteristics of the hall.

14) Uniformity : Uniformity of sound is one of the important conditions of a good concert hall. The sound may be poor in some locations, for example, under deep balconies. Also sound can be poor where reflections cause defects like echoes. It is important to eliminate, minimize these locations where sound is poor to achieve uniformity in the hall.

15) Tonal quality : Tonal quality of a music hall can be expressed by its ability of not distorting the sound produced by the performers. The tonal quality of a hall is distorted when there is selective sound absorption. Tonal distortion occurs if the side walls or ceiling absorb some particular frequency, and remove it from the music. Also echo between two parallel walls, flutter echo, can cause the hall to lose its tonal quality.

16) Freedom from echoes : Echo is the delayed reflection loud enough to be perceived as a separate sound and it disturbs the listener. A high and/or focusing ceiling surfaces or a curved rear wall whose focal point is near the front seats or even

on the stage can be the reasons of echo. Echo from a rear wall can be prevented by dividing the wall surface into different sections, some parts tilted down, some up, and others to side directions. Echo is avoided when the sound is scattered and prevented from returning to the hall directly. The angle and number of different wall surfaces depend on the shape and dimensions of the hall.

The chart in Figure 3.1 below summarizes the interrelations between the musical qualities heard in a hall and the acoustical factors that affect those qualities.

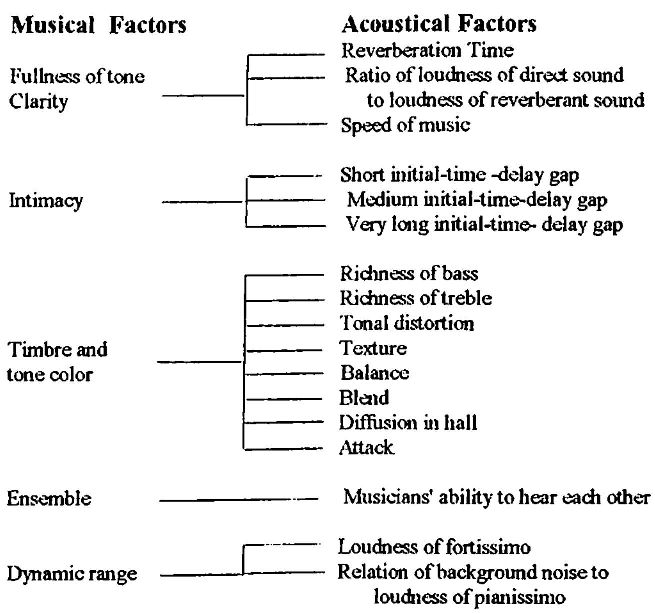


Figure 3.1 Chart Showing the interrelations between the audible factors of music (Beranek, Music, 43)

17) Freedom from noise : In the design of a concert hall the isolation of all external noise and noise caused by the listeners must be well handled. Noise may be in the hall due to traffic, subways, airplanes, ventilating systems, and movement of late-comers on stairways. Sound insulation techniques should be applied to lower background noise levels.

Subjective Music Conditions	Acoustical Properties of Room
Clarity and intimacy	1. Initial time delay gap (< 20 ms) 2. Shape and proportion (e.g., length to width ratio< 2, or use suspended sound reflecting panels) 3. Avoidance of deep balconies
Reverberance (or "liveness")	1. Volume (8.5 m^3 /person for rectangular halls, 13 m^3 /person for surround halls) to provide sufficient reverberance (1.6 to 2.4 sec at mid frequencies) 2. Shape and proportion 3. Furnishings and finishing (sound reflecting wall and ceiling) 4. Audience capacity and seat spacing
Warmth	1. Relationship of absorption at low frequencies to mid frequencies (bass ratio > 1.2) 2. Thick, heavy enclosing surface 3. Width of room (height to width ratio > 0.7) 4. Size and shape of sound reflecting walls 5. Coupled spaces (stage house, understage moats)
Loudness	1. Volume (and other reverberance properties) 2. Distribution of sound absorbing finishes 3. Stage enclosure and sound reflecting surfaces at front end of room
Diffusion	1. Large scale wall and ceiling surface irregularities, quadratic residue diffusers 2. Shape and proportion (e.g., narrow widths, large height to width ratios) 3. Finishes and furnishings
Balance and on-stage hearing	1. Size of stage enclosure (and use of risers for musicians) 2. Shape of sound reflecting panels near orchestra (stage enclosure design) 3. Distribution of sound absorbing finishes (and audience seating in surround hall) 4. Adjustability of overhead sound reflecting panels

Table 3.2.: Subjective music listening conditions along with room acoustics properties which influence the corresponding subjective judgments of music performance (Lawrence, Acoustics 98).

For a hall to be successful, its design must satisfy the subjective criteria. Subjective music listening conditions are the results of acoustic properties of a room, which are highly necessary for the full appreciation of performance (Table 3.2.).

3.2 OBJECTIVE CRITERIA FOR CONCERT HALLS

It is known that in many concert halls, seats in some areas have good listening conditions and others in the same concert hall are poor. Because of this reason it is necessary to obtain objective measurements of sufficient correctness to modify the acoustic conditions for such areas. Objective measures offer a description between design and subjective criteria. According to the behavior of sound in an enclosure, the design creates a sound field at the audience seating area. The properties of that area can be described in objective acoustic terms to evaluate the space quality. With the help of related objective measures, it is possible to obtain how design affects the sound field and how the listener will then hear it.

1) Reverberation Time : Reverberation time is the objective impression of liveness. It is the time taken for a sound intensity to decay by 60 dB after the sound source is switched off. In halls where reverberation time is long, music sounds longer. The musicians think of reverberation as a component of music. Reverberation is important in increasing the fullness of tone and the blend; it adds to the blending of instrument; and it diffuses the sound as it is distributed throughout the room. On the other hand too long reverberation time causes to a loss of clarity, the blending of unsuitable

orchestral part. It is possible to calculate this property during the design stage and it can be measured in the completed building (Beranek, Music 54-62).

Liveness in a hall is related to the reverberation times at the middle and high frequencies, above 250 cycles per second. Although reverberation time at the middle frequencies are used as clue of the liveness of a hall, reverberation time at higher frequencies has little effect on liveness (Beranek, Music 425-431).

Auditoriums for different purposes require different reverberation times (Figure; 3.2). Satisfactory listening conditions can be achieved in these auditoriums when reverberation times within the preferred range are achieved with the satisfaction in other important acoustical needs.

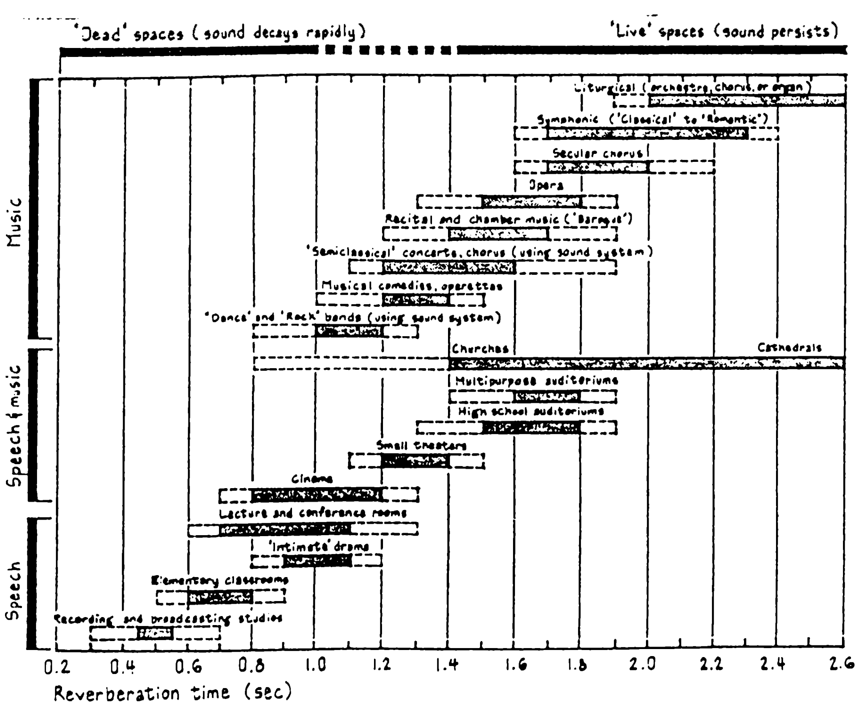


Figure 3.2.: The preferred ranges of reverberation time at mid- frequency (average of reverberation at 500 and 1000 Hz) for different activities (Egan 64).

2) Early Decay Time : Early decay time is also a measure of the sound decay like reverberation time. It is based on the first 10 dB part of the decay. Atal, Schroder and Sessler (cited in Barron 42) indicate that "...in a highly diffuse space where there is a linear decay, the values for reverberation time and early decay time would be identical. The early decay time is being used more than the reverberation time method for the determination of liveness."

3) Loudness : Both the direct sound and reverberant sound add to the total loudness in a concert hall. It is important to consider the reverberation as it contributes to the loudness with the direct sound. Loudness of a tone is related with the cubic volume of the hall, the reverberation time, and the sound energy. The reverberation time is longer and the cubic volume is small, the loudness of sound is greater. Distance from the source is an other factor affecting the loudness of the perceived sound in a concert hall (Figure 3.3).

Loudness
- volume
- reverberation
- primary reflections
- direct sound

Figure 3.3: Factors affecting the loudness of a sound in a concert hall (Moore 169).

Although the volume of the auditorium should be related to the number of instruments in the orchestra, the volume cannot be limited for economical reasons. It is possible to use electroacoustic devices when necessary loudness can not be achieved because of the volume of the hall.

4) Definition or clarity : In a hall with good definition the music sounds clear, and in a hall with bad definition the music sounds blurred. Definition is highly related to the initial time delay gap. The initial time delay gap must be short to add power to the direct sound.

Also the direct sound must be loud enough for each seat to have clarity for music. For this reason the audience must not be seated too far from the performing area and the floor must be sloped for the soundnot to be absorbed while grazing above the heads of audience. Also the reverberation time must not be too loud to mask the direct sound and there must be no echoes in the hall to achieve good definition.

The chart below (Figure 3.4) summarizes the necessary conditions to achiece clarity for the full enjoyment of music in a concert hall.

- Clarity
  - initial time delay gap
  - echoes
  - direct sound
  - reverberation
  - primary reflections

Figure 3.4: Factors affecting the clarity of a sound in a concert hall (Moore 169).

As initial time delay gap, the distance of listeners, the slope of floor, and the reasons for echo are related to direct sound and short path reflections, geometry of concert hall is important when definition or clarity is considered.

5) <u>Brilliance and fullness of tone</u> : Brilliance is achieved when the high frequencies are stressed and have slow decay. Brilliance is achieved when the initial time delay gap is short, the reverberation time for high frequencies are ideal, and loudness of the direct sound is high enough (Beranek, <u>Music</u> , 66-68).

Fullness of tone relates to the low frequency components in the decay. The presence of high frequency components and low frequency components in the early decay period can be measured.

Objective criteria for music must be handled together, because the interrelation among them, especially among the reverberation time and ratio of loudness of direct to reverberant sound are important for the degree of definition and fullness of tone in the hall (Figure; 3.5).

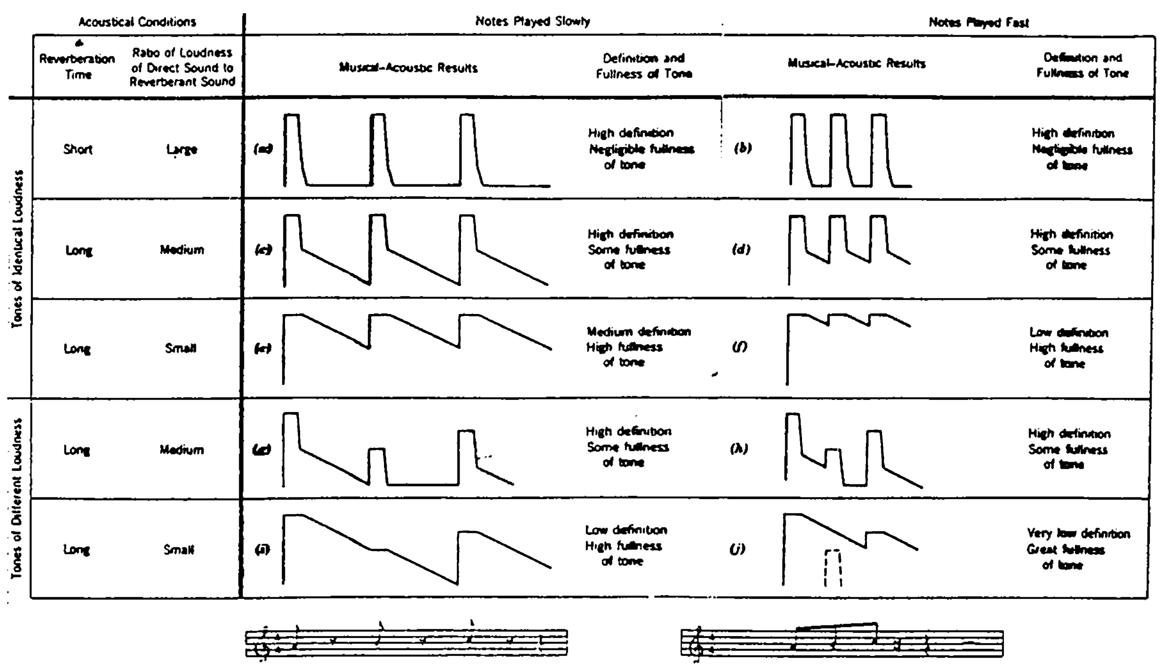


Figure 3.5.: Illustration of the interrelations among speed of music, reverberation time, ratio of loudness of direct to reverberant sound and the music itself (tempos are identical) (Beranek, <u>Music</u> 37-8).

4. DESIGN OF CONCERT HALLS

4.1 DESIGN OF SIZE AND VOLUME

<u>Size</u>: The sizes of concert halls are different from each other depending on the design, and architectural concept. The total seating capacity is the first concern in the design of a new hall as it determines the necessary size to envelop it. The sizes are getting bigger when larger seating capacities become necessary. Also seating area and its dimensions per person, are important factors in the design of a concert hall, which is necessary to achieve both comfort conditions for the audience, and building code requirements.

It is more difficult to have good acoustics in a concert hall when the size increases. Barron states that halls with seating capacities in excess of 2000 with good acoustics are very rare, even in the world wide context (44).

The maximum distance from which people can see the stage determines the length of a hall. As there is little chance to play with length of the space, it is only possible to determine the seating capacity by designing the necessary width for the hall. When the width of the hall increases, there is chance to seat more audience. However a wide hall with a high ceiling does not provide early reflections which are essential in achieving intimacy for the sound in the hall. This situation creates serious acoustical problems in the design of concert halls.

The width of a hall is very important for the composition of the direct and reflected sound. It highly affects the total quality of the sound coming to the listener's ear (Figure 4.1). The size of audience, the layout of seating, the number and size of the balconies, the economics, and the acoustical considerations are the main factors in determining the width of the halls.

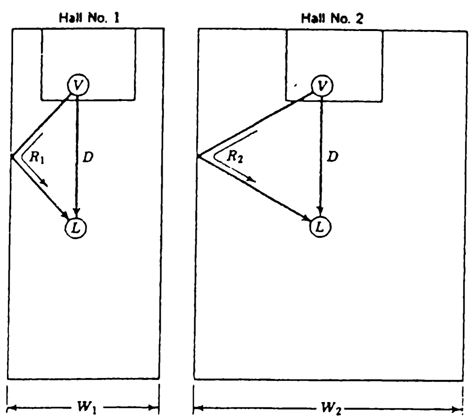


Figure 4.1.: Drawings showing the effect of hall width on the difference in path length of R and D. The direct sound travels path D from the V to the listener L. The reflected sound travels path R. The distance (R_2 - D) in hall no.2 is much longer than (R_1 - D) in hall no.1 (Beranek, Music 397).

The reflected sound becomes separated from the direct sound coming from the stage in a large hall as the time necessary for the sound to travel in the room is long. Also, in a large hall, the loudness of the direct sound that comes directly from the performer to the listener may diminish a lot in the far rows of seats. Moore says "...although the attenuation of sound due to distance in the case of a full orchestra is less than for a 'point source', the attenuation of sound from solo instruments follows the inverse square law..." and he adds "... the need to reduce distance from platform to rear seats for the weaker sounds of solo instruments is important..."(170). It is difficult for performers to fill the vast volume of space with their music when the room size is too large. Because of these reasons it is not easy to provide excellent acoustics for large halls.

The need to seat more audience for financial considerations also makes the size get bigger. When there is an increase in the size of a hall, the quality of the musical sound inevitably changes. But the degree of change, depending on size, can be decreased by the reflectors placed at necessary locations. It is possible to create a similar acoustical environment of a decreased width, and reinforce the direct sound with such reflectors. Sound can travel in shorter paths of a narrower enclosure created with the introduction of the reflectors to the space.

The use of reflectors in a concert hall may be required to meet the conditions of a good acoustics. These elements are useful, if correctly placed and designed. Whether they are vertical or suspended, the aim of the reflectors is to reinforce the direct sound to achieve the desired level of music for the full appreciation in the whole space. The frequency of sound and the angle of incidence, the material, shape and size of the reflector are the main factors affecting the process of reflection.

<u>Volume</u>: "The most desirable volume for a room is closely correlated with the design of the ceiling." says Knudsen (170). There is no fixed, ideal ratio between ceiling height and width and length of the concert hall. The ideal height, and therefore the

ideal volume per seat, is dependent on both the seating capacity of the room and the purposes of the room.

The ceiling height of a concert hall determines the whole volume of it. As the volume is an important parameter in determining the room's reverberation time, it should be selected in accordance with the requirements of the performance in the enclosure (Figure 4.2).

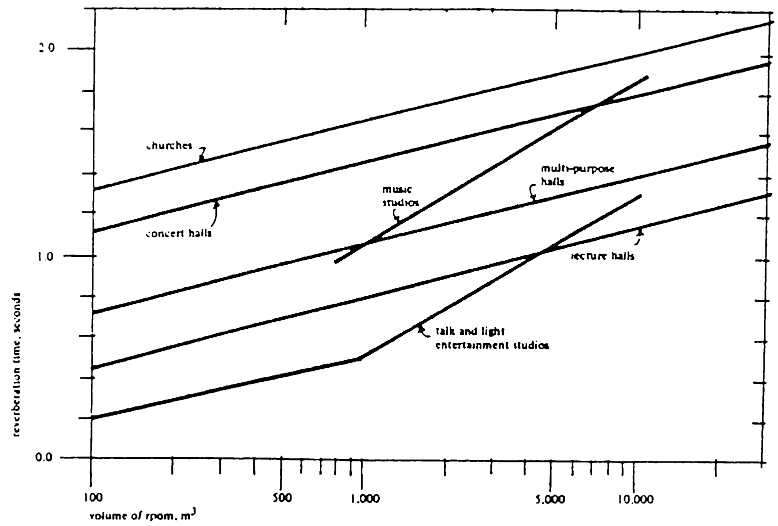


Figure 4.2.: Recommended mid-frequency reverberation times for auditoria (Lawrence, Acoustics 94).

A smaller volume in the design of a concert hall results with a shorter reverberation time. As the reverberation time equation is as follows T = 0.161 V \ A (Moore 164) (T=reverberation time (s), V= volume (m^3), A= area (m^2)), any reduction in the height of the ceiling of the hall, or any increase in the total absorption of the hall will end up with a harmful effect on the liveness of the hall.

Music is louder in a small hall than in a large hall. Cubic volume and surface reflections are the factors affecting the loudness of reverberant sound in a hall. The loudness of the reverberant sound is directly related to the reverberation time, but inversely related to the cubic volume of the hall. Beranek says "...loudness is some function of the ratio T / V where T is the reverberation time at mid frequencies with audience and V is the cubic volume"(541). It can be deduced that music in a hall may be too loud as the hall is either too small or too reverberant. On the other hand, music in a concert hall may be too weak if the cubic volume is too great, or the reverberation time is too short.

In concert halls, high ceiling is usually necessary when there is need to use balconies to seat more audience. Because of the high ceiling, there may be excessive time delay between reflected sound from the ceiling and direct sound. When this is the case, the introduction of suspended reflectors (either horizontally or at an angle) may be necessary to prevent the excessive time delay which causes problems.

4.2 DESIGN OF HALL SHAPE

4.2.1 EFFECT OF HALL SHAPE IN ACOUSTICS

The quality of the acoustics of an auditorium does not only depend on the reverberation time, volume and size but also on the shape of the enclosure. A geometry is necessary for an acoustic reflection to occur in the hall, and mostly, the shape of hall is the result of this necessary geometry.

For music, the sound level is important for the listener. This level usually depends on the orchestra and the music type, but the received sound is highly effected by the design of the hall shape. Edward states that:

> ...listener preference relates in many ways to what is currently being called 'lateralization of the sound field' and thus to the shape of room. Increasing the lateralization of sound means increasing the ratio of sound intensity that arrives from the listener sides... Needless to say lateralization is not the only characteristic that affects the listener preference; however the suggestion is perhaps less surprising when one considers that the best acoustics in concert halls are usually found farthest from the stage (in the rear of the top balconies), and that often the worst acoustics are much nearer the stage (in front of the main floor seating area) (133).

The reflected sound, coming from the sides of the hall, is one of the important elements in achieving best acoustics. Especially, the reflections from the sides of halls provide 'lateralization' of sound in the space which is the most required factor for the listeners to enjoy the subjective criteria envelopment, loudness, intimacy, and warmth of music in the space.

4.2.2 HALL SHAPES FOR MUSIC

Halls generally have the following shapes:

- Rectangular
- Fan

- Geometric (polygonal, circular, etc.)
- Horseshoe

Rectangular Shape: The rectangular form is a box in proportion, that has the audience grouping in the center of the space having aisles generally at the sides. The hall width is usually small and there is high cross reflection occurrence between the side walls. As all seats are close to the reflecting surfaces because of the limited width, the audience have chance to receive a good blend of sound. Barron states that, the sense of reverberation and envelopment by the sound are very good (44-46). Also with the early reflections it is possible to have high degree of loudness and intimacy.

It is difficult to enlarge the dimensions of the traditional rectangular hall as this might cause seeing problems. One solution to enlarge the capacity, with good vision, is to use balconies. However, the use of side or rear balconies may cause problems to the audience seated beneath.

Fan Shape: The fan shape halls are mostly preferred when there is need to seat more audience. It is possible to place more people closer to the sound source with a clear vision in a fan shape hall than a rectangular hall, but there are some acoustical problems to be handled when this hall shape is chosen.

Because of the plan shape, the rear wall of the auditorium is generally constructed as a concave curved surface. The most obvious problem with the fan shape is that concave rear wall, which produces a focused echo back to the stage. One of the solutions for this problem can be the tilting the rear wall to reflect sound down on the audience. Also placing absorbent material or designing the wall surface in a way that will diffuse the incident sound can be other solutions.

As the width is much at the rear of the hall, some seats are left in the center rear of the concert hall having few early reflections from the side walls. This can lead to different sound quality between sides and rear center.

The possibility for multiple reflections is much reduced in the fan shape. This problem affects the quality of the received sound and causes the lack of the feeling of surrounded by sound. It also causes to receive a low level of late sound towards the rear of the hall because of the width.

For the fan shape hall "... the sound is more frontal than lateral and the sense of reverberation is diminished by the limited degree of diffusion" says Barron and adds "With these halls pronounced variations in the quality can often be observed, with at times a dull sound towards the rear of the hall seating and a lesser sense of reverberation at seats distant from the stage" (85) .

Geometric Shape: Geometric shapes of hall can be in circular, elliptic or polygonal formats. In these hall shapes, highest attention must be paid to the crossing of reflections which may cause unwanted focusing problems. These problems can be eliminated with an irregular geometric shape (i.e., hexagon, octagon, having different dimensions for each side) by applying carefully angled walls and introducing elements that can diffuse the sound.

Circular and elliptical shaped floor plans may cause unwanted focusing effects, non-uniform distribution of sound, and echoes. In both elliptical and circular plans, the acoustical conditions, or acoustical defects can be greatly improved by the addition of cylindrical, angular diffusing surfaces, and irregular application of sound absorbents (Knudsen, 161-62).

The elongated hexagon (called as coffin shape) gives designer chance to place a larger audience than a rectangular if necessary. Also, to achieve better cross reflection characteristics in a coffin shape is more easy than a fan shape hall (Lord and Templeton 62).

Horseshoe Shape: The horse shoe plan is not so popular in symphony concert halls. Satisfactory reverberation time can be achieved when the hall is enlarged enough but this may create poor reflection patterns. Also, like the fan shape hall, there may be focusing problems caused by the concave rear wall.

4.2.3 SPECIAL ACOUSTICAL PHENOMENA ASSOCIATED WITH THE SHAPE OF CONCERT HALL

According to architectural style or preferences, the shape of halls are different from each other. Shape is one of the design criteria that helps people to distinguish one hall from the other. The hall shapes may add to the acoustical quality of the space if correctly chosen and treated, but may create some problems also.

Certain amount of reflected sound is wanted not only by the audience but also by the performers in the concert halls. When reflective surfaces are properly designed, it is possible to obtain sound reinforcement for rear seats with the help of the reflected sound. Also these proper reflective surfaces, provide good diffusion of sound in the enclosure. However, when not well controlled, reflected sounds can cause some acoustical defects like echoes, room flutter, whispering galleries, and dead spots.

Echoes: The sound path, that reaches to the listener, having reflections from the boundaries of the enclosure travels more distance than the sound path which comes by the direct path. If the difference in these two path lengths creates a time difference of about 0.06 second, the delay in the arrival of the reflected sound is enough for a listener to hear it as a separate sound, as an echo. Echo is a repeated sound signal that gives the impression of coming from somewhere other than the position of the true source. Echo creating reflected sound must be diffused, or attenuated by means of absorption to eliminate the negative and dangerous effect on the hall's acoustical quality. Large areas of absorbent surfaces must be avoided in curing the echo if possible, as these areas may effect the hall's reverberation time on the conversely.

Flutter Echo: It usually occurs between a pair of parallel (opposite) walls in a room, or between the ceiling and floor. Flutter echoes can be eliminated by avoiding the use of parallel pairs of surfaces or by breaking up the uniformity of such surfaces with doors, windows, hangings, or patches of absorptive materials.

Whispering Galleries: These are usually curved surfaces where reflections of high frequency sound travel or creep around a large concave surface.

Dead Spots: Dead spots are the localities where the sound level is not enough for satisfactory hearing. This areas are usually seen in large halls. Reinforcement and especially directing of sound must be provided to these areas with the help of reflectors.

4.3. DESIGN OF STAGE

Providing good acoustics for the audience is not enough to have an acoustically successful concert hall. Meeting the requirements of the musicians is also important in supplying good acoustic for the hall. The platform for the performers, with instruments and the surrounding surface finishes, must be designed carefully to support the overall acoustics of the space. In a well designed stage the musicians have the ease of hearing each other and have the chance to feel their own instrument during the performance. Also the stage must carry the sound from the players to the audience without changing its original character.

4.3.1 MUSICIANS' CRITERIA

The acoustics of a concert hall, in which the music is being presented, also affects the way in which it is performed. Most musicians are sensitive to the sound of their music and automatically adapt their performance according to it. While designing the stage area, the musicians themselves have two important measures to be satisfied; first, the stage should answer to their instruments and, secondly, they should be able to hear each other. If hearing each other is not provided for the instrumentalists in an orchestra, it will be difficult for them to keep perfectly in time with each other and hard to follow the conductor's intentions to make adjustments during the concert. Rather than this they would not be able to sense the power of their playing as a group as they desired.

Lawrence, in Architectural Acoustics, states "In order that a performer should hear the response of the room to his instrument it is necessary that some sound should be reflected back to him from the listening area " and adds "however, care must be taken that echoes do not occur on stage from long delayed reflections. Reflecting surfaces around the orchestra, including overhead, will enable the musicians to hear each other" (130).

4.3.2 FLOOR SPACE, LAYOUT, AND RISERS

Blending and grouping players on the stage is also important in achieving successful results in stage design. When the musicians are spread out on a large floor having greater distance between them, the acoustic interaction becomes weak. Very wide or very deep stages create problems. When the stage is wide, an audience seated on sides of the hall hears the instrument near or closer to him, before he hears the sound of an instrument from the other side of the stage. This difference affects the blend which is necessary for the full appreciation of the music. Also it is difficult for the conductor to control and hold the parts of the orchestra in good ensemble when the stage is too wide. Moore explains that:

> If players were, for example, spread out across a platform the full width of a large concert hall, the audience, especially near the front, would be conscious of the fact that the sound of the violins had been separated from that of the cellos and the blend of the two groups would be diminished. The normal close grouping of players around the conductor and the limiting of spread by a fairly deep seating arrangement should therefore be maintained in designing the platform (174).

When the stage is very deep, the sound from the instruments at the back of the stage will arrive at the audience with an apparent delay after sound from front of the stage which again causes the similar blend problem of the wide halls. Beranek suggests all parts of stage must be fitted within a rectangle which has around 18 meter width and a 12 meter depth for a good ensemble (Music, 498) .

Also close spacing causes problems when one is near to a more powerful instrument. Problems due to these factors may be avoided by adjusting the layout, by the use of risers, in design of the stage etc. (Figure 4.3).

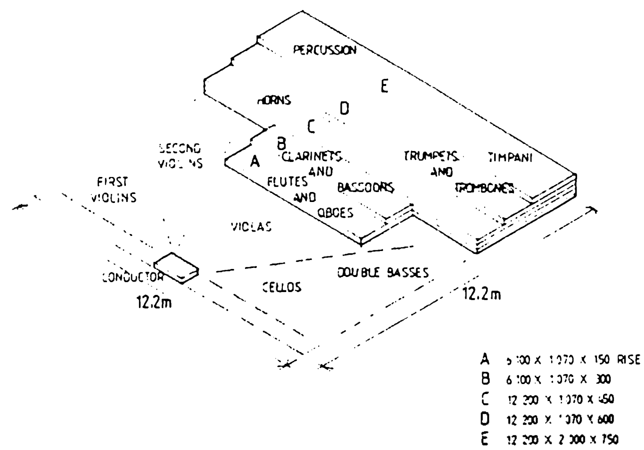


Figure 4.3. : Stage arrangements and the use of risers (Lord and Templeton 68).

The direct sound, from the instruments, propagates more freely between the players when they are separated, and elevated. In many concert halls, the instruments at the rear of the stage are elevated above the floor level by risers. The placing of risers gives the listeners a better view of the orchestra. Beranek, Johnson, Schults, and Watters say " This arrangement...affects the balance between brasses, woodwinds, and strings. The risers are also believed to enhance the sound of the lower string instruments" (1250).

The risers eliminate the acoustical problems which can be caused by being hidden behind another member of the orchestra. As the dimensions and required spaces are varying with the type of instruments, and with the size of the orchestra, flexibility in depth, size, and placement in the riser design is important to provide effective use of space when necessary.

An investigation cited in Beranek, Johnson, Schults, and Watters shows the effect of risers vary from note to note, changing from 4 dB gain to 4 dB loss between adjacent tones. But the result of the investigation suggests an increase in sound output and adds " All the musicians reported that it was easier to play when they used the risers; the tone quality increased in richness with the risers,..."(1259).

4.3.3 STAGE ENCLOSURE AND THE PLATFORM

In halls having a stage house, an orchestral shell is necessary to envelop the orchestra. Stage enclosure for performers must be designed in a way that it should respond to the requirements of the musicians. Lawrence, in Acoustics and the Built Environment, states "...they prefer to receive some sound reflected back from the audience area in order to perceive the 'room effect' "(198). It is important that the space in which the performers are located is to be designed as part of the main space of the auditorium. If it is designed as a separate space, there will be a lack of contact with the audience, and there will be differences between the two parts of the design although they are the two halves of the whole. The introduction of well designed reflectors, properly selected finishes for the surfaces, and suitable geometry of the stage enclosure are necessary features in achieving good acoustics for the space.

The empty volume, if there is, above the stage is a good absorber of high frequency sound. Much of the sound energy will escape towards these areas. Placing musicians behind a proscenium arch on a stage, without taking necessary precautions, and without designing proper stage enclosure create problems in preservation of the good acoustics and sound quality for the whole space.

Side and back walls of the stage:

Blending the sound in the stage enclosure is an important concern for the musicians and for the audience to have a successful performance. Combination of the total sound can be achieved by the help of stage reflectors. Reflective surfaces placed around the orchestra must be designed in a way to reflect the energy back to the performers. If they are designed properly they will provide clarity, and envelopment to the stage area (Lord & Templeton 65-67).

Surrounding the performers with sound absorptive material must be avoided. The use of absorbent material for the enclosure may cause loss of projected sound reaching the audience. Also it becomes difficult for the performers to hear each other, when absorption occurs at the stage during the performance.

Beranek (Music 501) says the best material to use around the side of a stage are plaster on brick or plaster on masonry block. Material selection can be different for some reasons but the side surrounding of the stage should be heavy enough to prevent serious loss short wavelength sound caused by the absorption. The amount, type and location of applications for stage enclosures must be designed with the arrangement of the instruments on the stage.

Rather than the side walls, reflectors can be used vertically behind the players. These vertical elements may also contribute to the total blending of sound as well as providing additional power when needed. Again the size and material of the reflectors must be decided depending on the frequency range to be controlled.

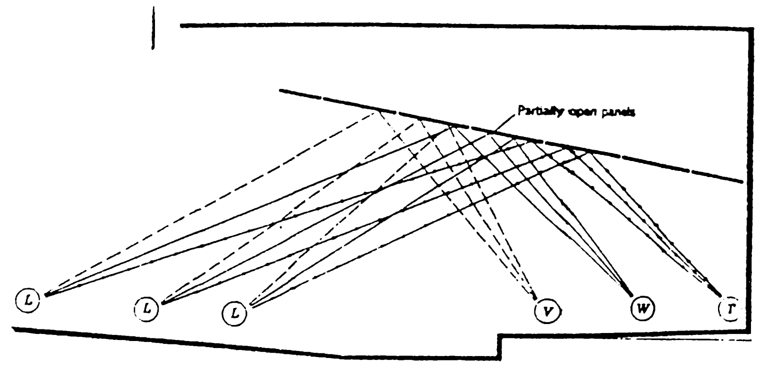
<u>Ceiling reflectors over the stage:</u>

When people come together for a performance, it is essential that all members of the orchestra hear each other. Without a good sound reflecting ceiling overhead, it is difficult for members of orchestra keep in time.

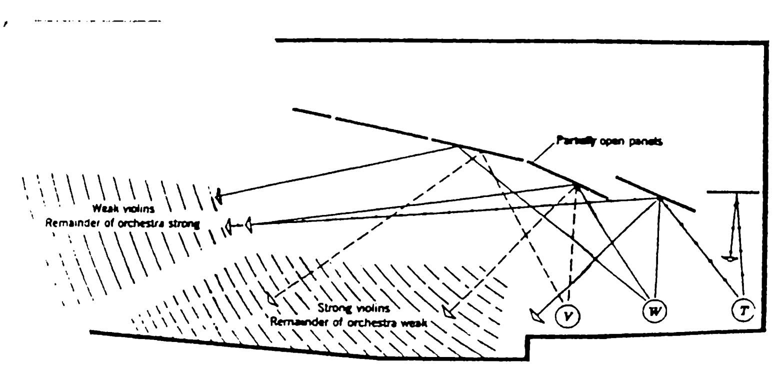
Moore argues that, a reflector above the players is the best way to achieve the necessary sound to be reflected back (176). This reflector will project the sound of each instrument to all the other players in the group. It can be placed close enough to the performers, but it must not be parallel to the horizontal plane of the platform, to eliminate the danger of standing wave patterns.

Like Moore, Barron also states that "...the most effective surface for providing early reflections on the platform is the ceiling" (55). In halls with open laid platforms and high ceilings, it is often necessary to suspend an array of reflectors over the platform. These overhead reflectors are useful to overcome the height important for adequate volume being too great for musicians to maintain ensemble. Under such reflectors, the musicians will hear each other well with the help of the early reflections. The continuation of the ceiling reflectors over the front part of the audience area helps to the projection and distribution of the sound from the stage to the hall (Figure; 4.4).

Also Lord and Templeton argue these reflectors help the audience to live the clarity in the work to a some degree (67).



(a)



(b)

Figure 4.4. : (a) Sketch of the ceiling reflector over the stage that provides orchestral balance on the main floor of the auditorium. The design shown here is intended to be illustrative and is not recommended for adoption without further study. V , violins; W , woodwinds; T , trumpets; L, listeners. (b) Sketch of the ceiling reflectors that provides poor orchestral balance on the main floor of the auditorium (Beranek,Music 500-501).

Slightly convex reflectors are more effective in diffusing the sound uniformly in the space. Also to a certain degree, diffusion for reflections from surfaces surrounding the platform is required to eliminate sound concentration. The disposition of the reflectors asymmetrically, or achieving flexibility to supply for different layouts can be desired for special performances.

The loudness balance between instruments at the back and front of the stage can be a problem. The lack of reflecting surfaces in the forward part of the stage creates this type of problem. Proper orientation of the ceiling panels and selection of proper materials for sound absorption can overcome this defect.

Stage platform:

The design of the stage floor is a difficult concern for acoustics, as there are several suggestions for the solution to it. One view cited in Beranek, Johnson, Shultz, and Watters suggests "... if the stage floor is thin, vibrations will be picked up from the pegs of cellos and double basses and increased low -frequency sound will radiate to the hall,...". On the other hand another view cited in the same paper discusses "...any kind of thin structure surrounding the sound source will resonate and absorb low frequency energy from the sound field and that the stage floor thus be heavy and rigid" (1250).

As a result, it can be concluded that: Whatever the construction is, in order to have a floor acoustically alive, the floor material and its application is to be decided carefully. Construction of the platform floor is of necessity for the successful play of instruments in contact with the stage, such as cellos and double basses. As Lord mentions, the point loading of the piano legs is of particular concern, when the design of platform is studied (45) .

4.4 DESIGN OF THE HALL

Design of a concert hall, considering its acoustics, is a complex work. Within the enclosure, design of every element has enormous effects on the quality of the music perceived by the listeners. Music is not only a perceived sound from the performing area, but a complex phenomenon with its reflected, reverberated, absorbed, and direct components, within an enclosed space. Each reflection and its path has a special effect on the quality of the performed sound (Figure 4.5). Because of that reason design of walls, ceiling, floor, seating groups, and stage are important elements and must be handled carefully in the design of a concert hall for satisfactory results.

4.4.1 FLOOR PLAN

The layout of the floor plan is the first step of a design for an auditorium and includes the proper placement, and grouping of seats. It is important to arrange the seating area having good listening conditions with the good distribution of sound from the source. Requirements for the good visibility also plays an important role in the design of the seating area. Placing the audience near the stage is necessary for both obtaining good visual and acoustic conditions. The size and shape of the seating area are the factors effecting the length and width of the concert hall, so the floor plan of the hall.

Satisfactory level of loudness and good distribution of sound are determined almost by the shape and the finishes of the room. Hearing sound loud enough and have it uniformly distributed are the most important expectations from the hall. Locations receiving too much or too little sound due to focusing or reflected sound, create unsatisfactory conditions. Also existence of a seat, in which everything is heard twice due to the long delayed reflections, is not a desired case in a concert hall.

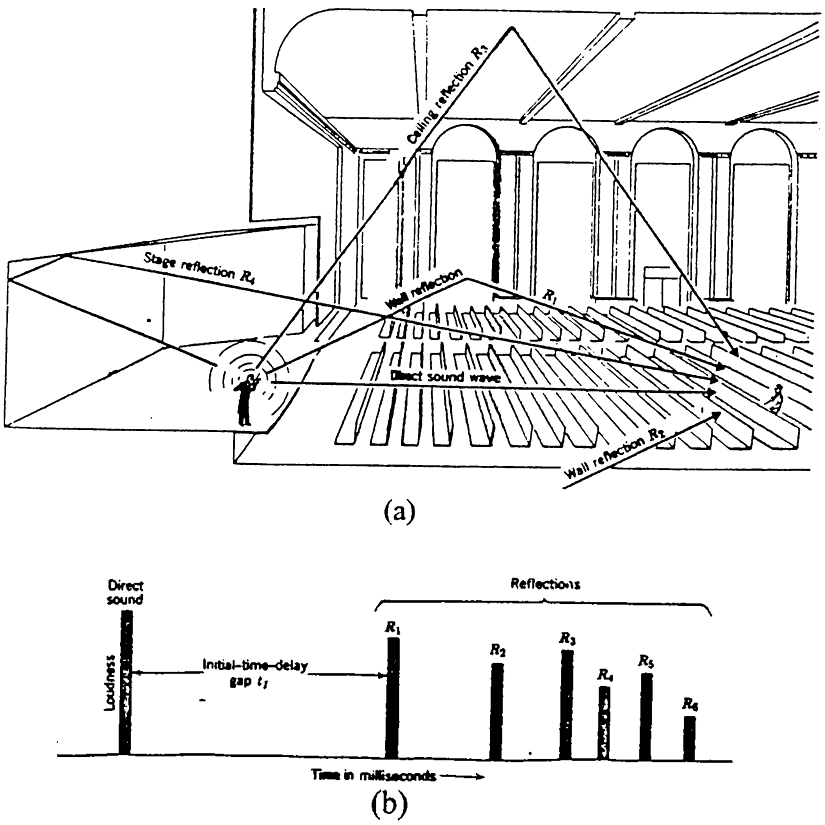


Figure 4.5. : (a) The paths of direct sound and several reflected sound waves in a concert hall. Reflections also occur from balcony faces, rear wall, niches, and any other reflecting surfaces. (b) Time diagram showing that at a listener's ears, the sound that travels directly from the performer arrives first, and after a gap, reflections from the walls, ceiling, stage enclosure, and other reflecting surfaces (R_5: balcony front, R_6: rear wall) arrive in rapid succession. The height of a bar suggests the loudness of sound (Beranek, Music 27).

Focusing effects, non-uniform distribution of sound, and echoes are the common defects seen in the circular and elliptical shaped floor plans. The floor plan may vary for many different concert halls, and there may be different acoustical defects present for each of these floor plans. Whatever the shape of the hall and the floor plan, it is possible to achieve good acoustics if the reasons of the defects are determined and necessary design solutions are provided.

In addition to the side walls, balcony surfaces, and seats, there may be other architectural elements used in the space which are parts of floor plan. Column like structures, piers, and niches in the space may not seem to change floor plan, but may be dangerous for the acoustics of the space if they are not designed and placed properly. When a sound wave hits these type of freestanding or protruding surfaces in the space, depending on the size of the obstacle, the sound wave can be reflected, diffracted or diffused. The material of the obstacle is an other important concern like the size, as absorption of sound is closely related with it.

When some part of the incident energy is turned about and travels back towards the direction from which it came, reflection occurs. The wavelength of the incident sound, the size and surface of the reflector, and the angle of incidence are the factors affecting the type of reflectance from a surface. For a specular reflection (angle of incidence is equal to the angle of reflection) to occur, the dimension or the irregularities on the surface of the reflector must be at least at the same size of the wavelength of the sound wave hitting on it. In case of waves being scattered in all directions after they are incident on a surface, diffusion of the sound wave takes place. Diffusion is a type of reflection and it is the scattering of sound in all directions.

If the obstacle, in the line of straight propagation is not large compared to the wavelength and not too small to be ignored, the sound may reach the back of the obstacle by going around it. This is the case of diffraction of the sound wave after incident on a surface. When the obstacle on the way of the sound wave is very small the sound wave seems to ignore it, and if the obstacle is very large, but not as the wavelength hitting on the surface, the sound waves are shielded and sound shadows are formed behind the obstacle. When a sound wave looses some of its energy after hitting a surface, absorption of sound is seen. All materials in the construction of building absorb some sound, but proper acoustical control requires the use of materials that are chosen to function as sound absorbers. Reflection, diffraction, diffusion, and absorption of sound in the space must be considered in the design of concert halls especially when there are additional architectural elements determining the floor plan of the space.

It is a good design approach to use the floor area which has the best acoustical environment for seating and to use the poorest areas for non-listening purposes.

4.4.2 CEILING

The ceiling must provide favorable reflections of sound, especially for the seats far away from the stage. It is important to reinforce the sound reaching the rear parts of the concert hall with the help of reflected sound. Because of that reason the ceiling must never be sound absorptive unless it is strictly required. The height, design, and material of a ceiling over a hall determine the acoustical quality of the reverberant, reflected, diffused, and direct sound in the space. The ceiling of a hall can be in different shapes, and be designed in many ways, but it must be hard and sound reflective.

It is necessary to arrange the optimum dimensions for a ceiling reflector to achieve the best results from the reflection of sound. Sound can be reflected in a way similar to light, with the angle of incidence being equal to the angle of reflection . But for this phenomenon to be true the reflecting object must be at least the same size as the wavelength handled.

The sizes of the reflectors for the ceiling are critical for the low frequency sound which have large wavelength. Diffraction occurs if the size of the suspended reflectors are small than wavelength of the low frequency sound. The reflection of high frequency sound is easy when compared to the reflection of low frequency sound. While high frequency sound can easily be reflected with forming sound shadows behind the reflector, the low frequency sound may bends around the reflector because of its large wavelength compared to the size of the surface. Because of that, the dimensions of the ceiling elements must be handled carefully to end up with good results.

The ceiling height of an auditorium is also important in the design of concert halls. As the ceiling height determines the volume of the hall, the reverberation time is directly effected by this factor. If the ceiling of an auditorium is too high and because of that excessive height, if the reflected sound follows the direct sound with a path of 17 m, loss of clarity may be seen in the space. Not only will the volume per seat be excessive, but also long delayed reflections from too high ceiling surfaces will cause problems and may be a source of echoes.

Suspended panels can be used to lower the ceiling to eliminate long delayed reflections and eliminate problems of echoes. It is useful to design openings between these suspended panels allowing circulation for the sound through the spaces above and below them. This type of application will help to preserve the necessary reverberation time required in the hall although the ceiling seems to be lowered by the installation of the suspended panels.

Concave surfaces such as domes, cylindrical arches, and barreled ceilings should be avoided where possible, as there may be serious acoustical problems of focusing. If a concave surface, a dome or a vault, is decided as the ceiling of the space, special surface treatment must be applied to the ceiling to avoid the problem of focusing. Simplest way to eliminate this problem is covering the concave curved ceiling with sound absorptive material (Fig. 4.6 (a)). But special care must be given for the selection and application of materials to achieve equal absorption for the high and low frequency sounds. One of the drawbacks of this system is the reduction in the reverberation time of the hall because of the absorption, and the other is the elimination of sound reflection to certain part of the space. Complete lack of ceiling reflections is a serious defect for the musical performances. The second method can be breaking up the concave curved surface into small scattering surfaces (Fig. 4.6 (b)). This system may change the focused reflection into diffuse reflection. The dimensions of the scattering surfaces must be designed related with the wavelength of the sound. If the concave ceiling is required just for visual reasons, application of a false, curved surface which is acoustically transparent can be a design solution (Fig. 4.6. (c)).

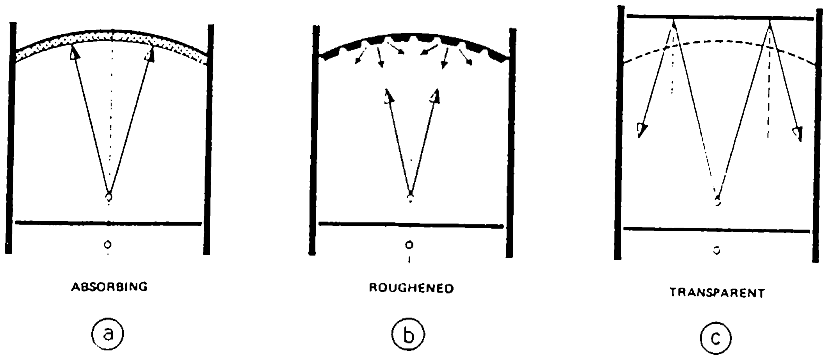


Figure 4.6. : Methods for avoiding focusing in curved ceiling surfaces: (a) by absorption; (b) by breaking up the focusing surface; (c) by making the visual domed surface acoustically transparent (Cremer and Muller 1: 62).

The law of reflection can be used to determine the most useful angle of inclination of ceiling which will reflect sound to the far away parts. Also in order to avoid flutter echoes, ceiling should not be strictly parallel to the floor especially when it is totally smooth. If the ceiling and floor are both smooth, parallel, and highly reflective, the flutter between the floor and ceiling will be very noticeable and may result with highly disturbing conditions.

Ceiling of a concert hall has other functions besides providing necessary sound reflections. The ceiling surface is interrupted by lighting fixtures and sometimes by air-conditioning outlets. It is not a good design solution to place so many technical equipment in the ceiling. Also rough or highly modulated ceiling surfaces are not desired as reflections can be scattered to locations where they are not needed (Cremer and Muller 1: 65-70).

4.4.3 SIDE WALLS

The side walls of a concert hall may not be only acoustical elements in the space, but may also be structural ones that carry the upper structures of the hall. The properties of the side walls depend on the accessibility to the space, shape, seating capacity, the design of architect, and applications elements related with them.

In a concert hall, the passage of sound beyond the walls of the space is not preferred, but rather it is important to conserve the sound by keeping it in the space. Because of this reason the walls must be hard and heavy to keep the sound inside for the pleasure of listeners.

The side walls are also as important as ceiling in reinforcing the sound that reaches the rear parts of a large concert hall. The reinforcement by the help of the side walls are especially desirable for auditoriums in which a sound amplification system is not used. An angled surface, or a projection on the wall must be designed so that it should reflect sound to those seats where the sound level is not adequate. The law of reflection can be used to determine this angle. The side walls should be designed so that the sound they reflect to the audience will not be too long delayed. Sometimes some parts of the side walls may be the reasons for probable echoes or unwanted long delayed reflections. When this is the case, this part of the side wall should be designed in a way to diffuse the sound, or be covered with highly absorptive material not to reflect the incident sound causing problems.

Texture, the sound reflection patterns at various locations in a hall, is closely related with both the initial time delay gap and the order of reflections that follows the first reflection. Beranek, in Music, Acoustics, and Architecture , claims that "Good texture requires that there be five or more reflections or relatively uniform spacing within the first 70 milliseconds after the arrival of the direct sound, with each successive reflection slightly lower in amplitude than its predecessor." Because of that, the detailed shapes of the walls and the ceiling must be designed carefully as they are highly effective surfaces for texture in a concert hall (448- 450).

Warmth is another necessary criterion to exist in a concert hall and side walls are significant in achieving it in the space. Warmth is achieved when the ratio of the reverberation time at low frequencies to that at mid frequencies is necessarily large. To obtain this ratio, selection of appropriate interior finish material are very important in the design for the low frequency sound to exist in the space.

4.4.4 REAR WALL

The relationship between the size of the reflector and the wavelength of sound is the first factor affecting the reflection from a surface. Convex surfaces are known better reflectors than plane surfaces as they disperse the sound to a wide area. On the other hand concave surfaces are known as dangerous reflectors as they focus sound.

In the design of an auditorium, large concave, or flat sound reflecting rear walls should be avoided. Concave surfaces, as well as a flat sound reflecting rear wall, unless properly designed, can lead to focusing effects, echoes, and delayed reflections in many auditoriums. These harmful reflections can be eliminated in several ways. By introducing a splayed surface between the ceiling and the rear wall, application of sound absorbing material on the rear wall, or designing surface modulations can be some of the design possibilities to eliminate these unwanted harmful reflections (Figure; 4.7).

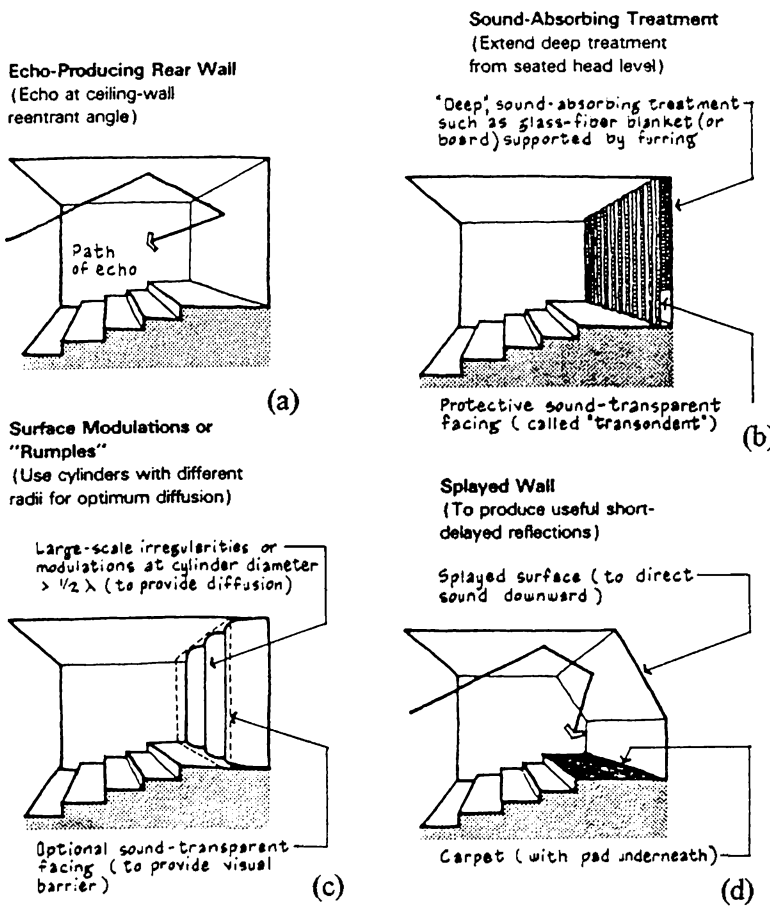


Figure 4.7. : (a) Echo producing rear wall
(b) Same rear wall with sound absorbing treatment
(c) Same rear wall with surface modulations
(d) Splayed wall (Egan 104)

4.4.5 SEATING

Seating is one of the most important elements in the design of concert hall. Seating arrangement, type, and density are highly effective on the attenuation, absorption, and distribution of sound which determines the quality and appreciation of music in the space. Because of its absorption characteristics, seating and arrangements of it play an important role in determining the hall's reverberation time.

The seating used in concert halls can be chosen from the following types:

1. Removable bank of seats
2. Folding type seats or bench risers
3. Upholstered fixed seats

Among the three types, upholstered seats are suitable for concert halls both for the comfort of the audience during the performance and for providing the same absorption when the audience in the hall is less than the full capacity. Providing same acoustical environment during the rehearsals, when the hall is empty, is an important factor for the success of the performers, and for the hall to sound the same. Because of these reasons, the selection of proper seating units with proper material, has great effect on the acoustics of the concert halls.

After the total seating capacity is decided, the important consideration is the density which the audience is seated. The absorption of an audience is not related simply to the number of persons included. Beranek explains this fact as :

...that an audience absorbs sound in proportion to the total area of floor it covers plus part of the area that the aisles surrounding or contained within the seating area. An audience does not absorb sound in proportion to the number of people in it (assuming that the hall is fully occupied). In other words more the audience is spread out the more sound it absorbs in the hall. Consequently the spacing of the seats is as important as the number of seats (485).

The optimum volume per seat for a concert hall can be determined from the lowest value that is necessary to meet the comfort and visual conditions to please the audience seated. Although it is desirable to have a low value of volume per seat, it is not a good design solution to achieve it by seating auditors so close to each other that they do not have comfortable legroom or by sacrificing other functional features. Beranek, in one of his article published in 1975 says the best concert halls of the world have seating areas in the range of 0.5 to 0.6 m^2 per person (1259).

Knudsen suggests "In an auditorium with a low volume per seat, if the furnishings (seats, carpets, draperies, etc.) have been carefully chosen, there may be no need for additional acoustical materials to control the reverberation time." And adds "... the lower the volume per seat, the higher will be the sound level in the room for a source of given power..." (170).

Widely spaced seats are more comfortable for the audience, but usually cost much for the acoustical quality and building. While center to center spacing and the row to row spacing of the seats must be as small as possible, consideration of current standards of audience comfort and safety must not be overlooked. If the seats in a hall are largely spaced, the width of the hall will increase in order to obtain extra floor area. As the width or floor area increases, the initial time delay gap at the listeners' ears may be too long which will result in undesired reflections.

For both sight and sound, it is an advantage to reduce the distance between the sound and audience as much as possible. In order for the loudness of direct sound to be high, listeners on the main floor should be seated within the 30 meters from the concertmaster if the walls and ceiling direct part of the sound into the balcony (Beranek, Music 489).

When direct sound waves, produced from the stage, pass over the audience at grazing incidence, they are absorbed. The audience, seated in front of another, is the main factor in the absorption of the direct sound, which causes a reduction in the sound level. In addition to the sound reduction depending on the distance, audience absorption of direct sound creates difficulties to maintain the desired sound level especially for the rear seating areas of a concert hall. In the design of seats, the general rule of good sightlines provide good direct sound propagation, is important. By elevating the seats a free flow of direct sound from the source to the listeners is provided. It is also advantageous not only elevate the seating area but also stagger the seats to form a more free circulation path for sound.

The first few rows can be level since they will have a good line for both sight and sound, and the floor begins to be sloped with the distance from the sound source to provide good vision and sound after these rows. The slope can vary for different sections of the hall as the distance between the source and the listener increases. Lord and Templeton state "Seating viewlines step up reasonably evenly if seats are on the flat floor up to the first ten rows, then say, from the eleventh to twentieth row set up at 10°, rear rows beyond the twentieth row 15°-20°" (64). Depending on the slope, the reduction of direct sound due to audience absorption can be different (Moore 147).

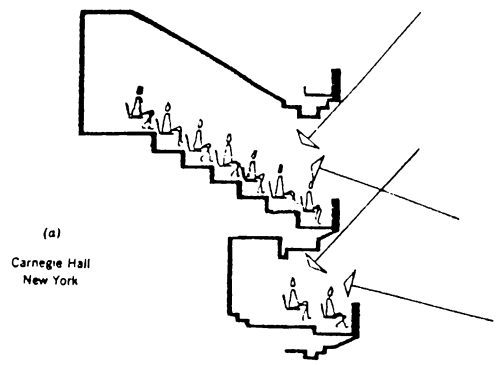
As the audience, or the upholstered seats are highly absorbent in a concert hall, the use of absorbent material in rest of the hall must be minimum to provide brilliance within the space.

It is also necessary to take into account emergency exit requirements, which will affect the distance between rows of seats, width of aisle and crossover lanes, etc. While playing with the slope of the sections continuous changes must be avoided as they are not comfortable to walk, and are not favored by fire authorities.

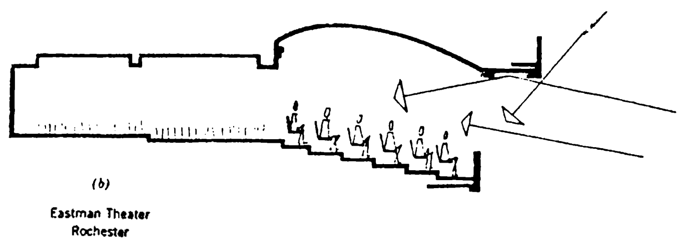
4.4.6 BALCONIES

Placing the audience closer to the stage is one of the aspects of a good hall. In order to accommodate a large audience, without excessive distances between the rear rows of seats and the orchestral platform, balconies are added rather than widening the hall. These balconies should also be designed to provide good sight lines to each seat.

Number, size, shape and placement of balconies may vary according to the type and audience capacity of the hall. But introduction of balconies to the space creates some acoustical problems both for these spaces and for the space under these areas.



(a)



(b)

Figure 4.8. : Two poor balcony designs : (a) upper balcony is poor, receives little sound from upper hall and opening is small. (b) poor balcony, very small opening and large carpeted area behind listeners (Beranek, Music 464).

Balconies which overhang audience seating are the features of the halls, but seating below these areas are disadvantageous spaces for acoustics. When people are seated under these overhang, they do not receive sound reflected from upper part of the hall. This creates serious problems especially when the balcony is deep and the mouth of the opening is not very high (Figure; 4.8.). Beranek suggests this is a serious problem among all the auditorium designs and explains "Deep overhangs are more damaging to symphonic music than to opera, since many styles of symphonic music require the overhead reverberation of the hall to convey the full effect of the composition"(465).

Good design of a balcony recess usually requires a shallow depth and a high opening (Figure; 4.9.). The depth should not exceed the height of the opening in a balcony (Figure; 4.10.). Also for a good design the reverberation time in the balcony recess must be close to that of the main part of the auditorium.

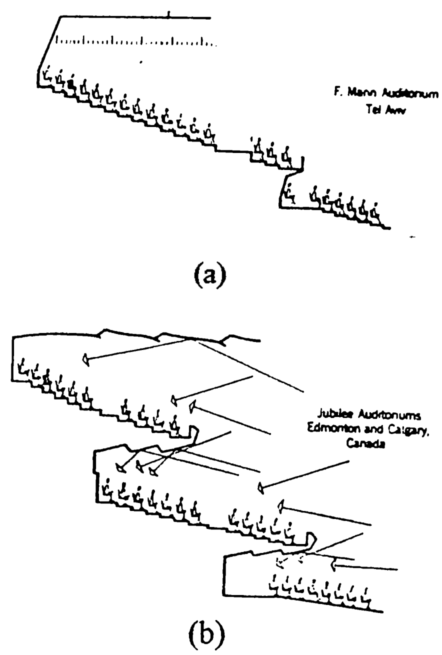
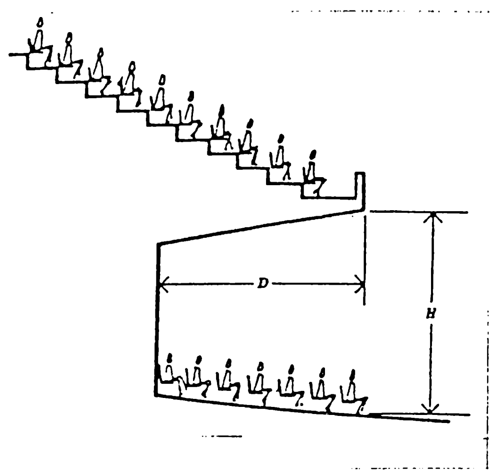


Figure 4.9. : Two satisfactory balcony designs: (a) no overhang; (b) little overhang and wide openings. (Beranek, Music 461)

The balcony front must also be carefully handled when the acoustical design of an auditorium is being worked out. Balcony fronts are generally large surfaces with small height. When they are not properly designed, these surfaces direct the reflected sound to seating areas with long delayed reflections, and they can give chance to occurrence of echoes. It is sometimes possible to use reflections from that surface to increase the sound level at the rear of the auditorium by tilting this surface downward. If using the reflections from the front of the balcony is not wanted, the front should be highly absorptive or should have an application on it to diffuse the incident sound without concentrating it in small areas.



D ≤ H for concert halls

Figure 4.10. : Recommended dimensions for a balcony design for a concert hall. (Beranek, Music 465).

5. CASE STUDY

5.1 BILKENT CONCERT HALL

The purpose of this case study is to evaluate the present acoustical situation in the Bilkent Concert Hall.

The present concert hall is a part of the building for Faculty of Music and Performing Arts. It is like a trapezoidal room in plan which is enlarged from the stage through the back rear wall. It consists of a main floor, a second floor having space for the chorus, side aisles and the main balcony, and a third floor which is only a small balcony like opening used for the control of technical equipment necessary for the activities in the concert hall (Figure 5.1).

The Bilkent Concert hall is separated from the study rooms by the corridors on the sides and a foyer . The back wall of the concert hall is constructed with wood panels, gypsum board (2 cm.), rock wool (10 cm.), brick wall (8.5 cm.) from inside to the outside. A 50 cm air space separates the wall of the concert hall from the inner wall of the building. Side walls of the space are also separated with an air space and have travertine veneering , plaster (3 cm), brick (13.5 cm.), rock wool (10 cm), and a brick wall (19 cm) from inside to the outside at the main floor. The finishing material used for floor and the stage is wood, and there are upholstered seats for the audience.(Figure 5.2)

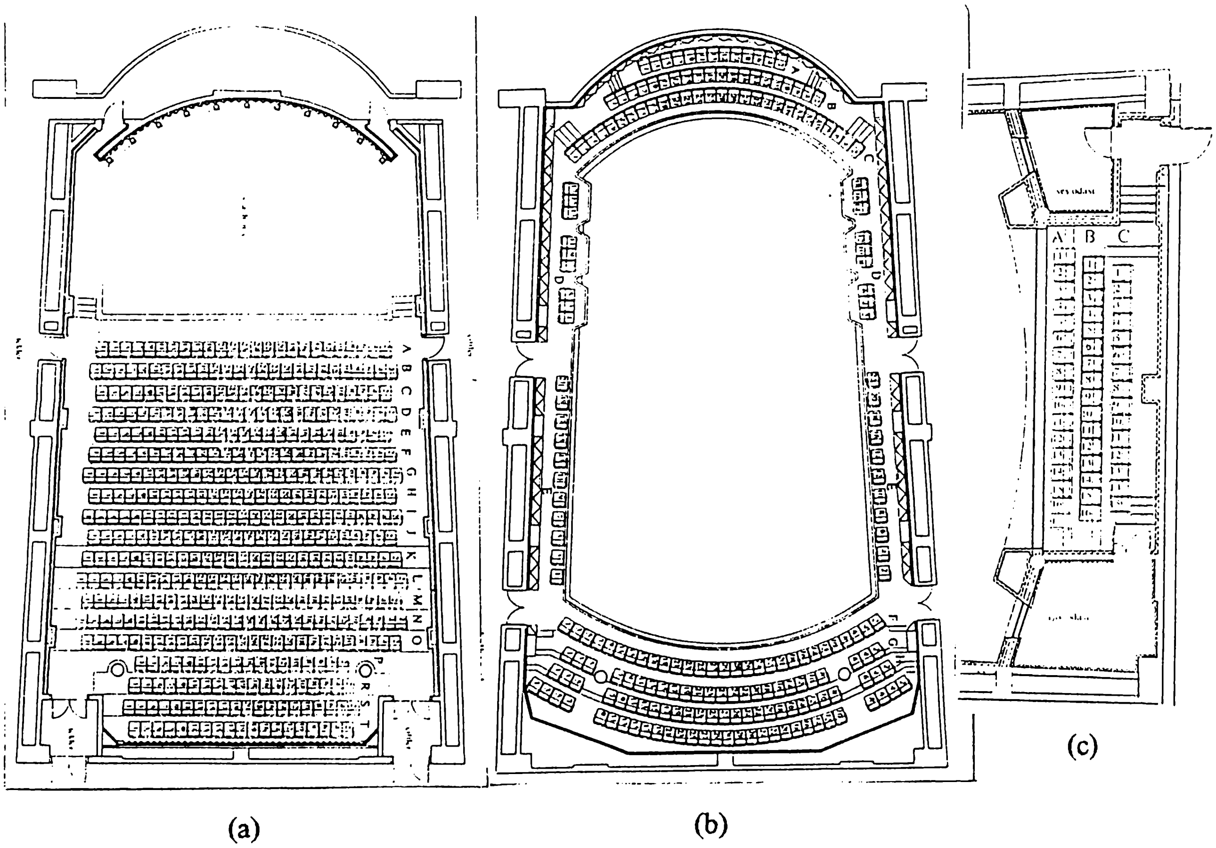


Figure 5.1. : (a) The main floor plan
(b) The second floor (balcony) plan
(c) The third floor (top balcony) plan

At the second floor of the concert hall, there are adjustable wooden panels, wood stripes (3 cm.), a gap (2.5 cm), rock wool (10 cm), and a brick wall (19 cm.) were constructed for the side walls. The back wall of the second floor was made from gypsum board (2 cm), rock wool (10 cm), again gypsum board (2 cm), and air gap following each other from inside to outside. The wall behind the chorus area is made from fixed, veneered chipboard, gypsum board (2 cm.), rock wool (10 cm.), concrete or brick wall from the inside to the outside. The floor finishing is again wood and the seats are all upholstered. (Figure 5.3)

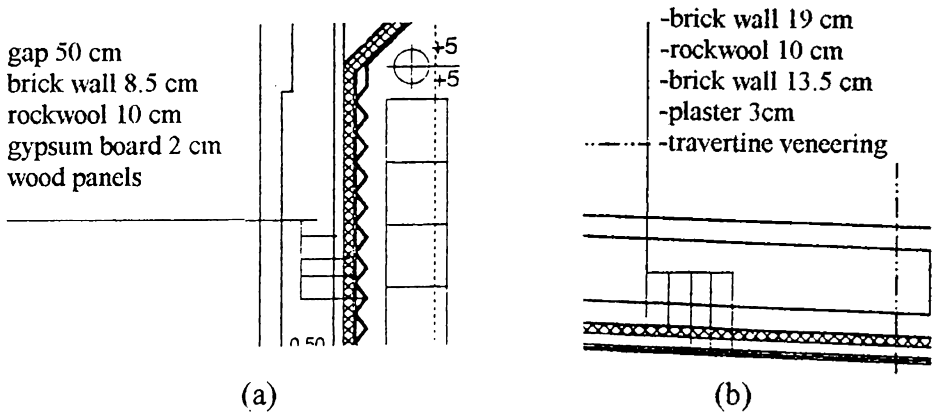


Figure 5.2. : The materials and their application (a) for the back wall, (b) side walls of the main floor of the concert hall.

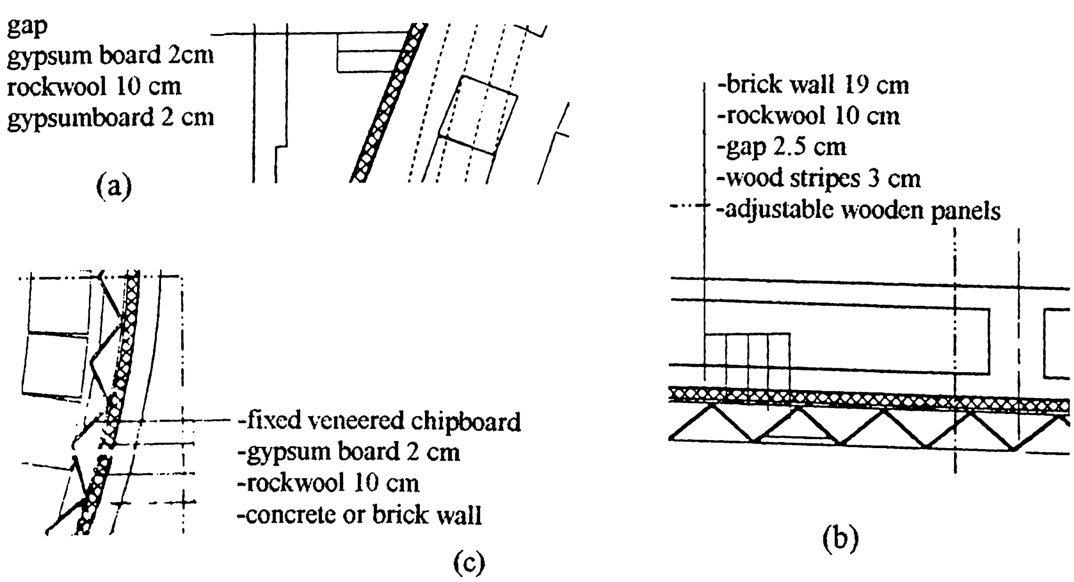


Figure 5.3. : The materials and their application (a) for the back wall, (b) side walls, (c) for the wall behind the seats reserved for the chorus at the balcony floor of the concert hall.

The stage has a curved wall made from fixed, veneered chipboard, rock wool (10 cm), and a concrete backing. There are plastered columns in front of this wall placed with the same angle with the curvature of the stage wall. The side walls of the stage is same as the rest of the side walls of the hall (Figure 5.4).

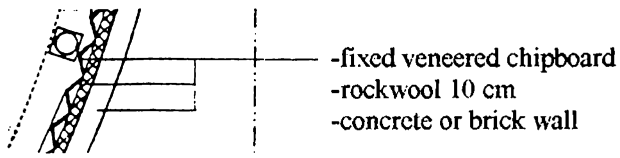


Figure 5.4 : The materials and their application for the stage wall.

On the main floor of the concert hall, there are six doors opening into the space. Two of them are placed at the rear wall, two are placed at the sides, and the last two are placed at the rear of the stage. Two pairs of doors are placed on the side walls, symmetrically, on the second floor.

The balcony fronts, and the ceiling are all plastered surfaces. There are lighting fixtures placed on the ceiling and on the side wall surfaces, under the second floor balcony and under the side aisles for the total illumination of the space.

There is a total of 685 seats in the main floor and the second floor of the concert hall. 473 are placed on the main floor, and 151 are placed on the second floor for the audience. The remaining 61 seats are reserved for the chorus, but are also used for seating the audience if there is no chorus.

5.2 EQUIPMENT AND METHOD

Description of the study:

The aim of the study was to figure out the sound pressure level distribution over the seating area of the main floor of the Bilkent Concert Hall. Eight different frequencies, and the white noise sound pressure levels were measured, and 'Landcad' computer program was used to print out the distribution pattern of sound pressure level over the seating area of the concert hall. The interpretation of the data was done wýth the help of these distribution pattern over the seating area of the hall.

Equipment:

During the analysis of the concert hall, sound was produced with a random noise generator (Bruel & Kjaer 1402). The set up of the random noise generator is as follows:

- Meter Time Constant (sec.) : 15
- Attenuator : 12 mV -60 dB
- Frequency Response : Weighted (-3 dB/octave)
  Linear (20 - 20.000 Hz) used for obtaining white noise
- Matching Impedance : 6 Ω
- RMS. Volts for Full Scale : 1.2 V
- External Filter : In / Out (to obtain white noise)
- Output Level : 3

The sound levels for different frequencies (63 Hz, 125 Hz, 250 Hz, 500 Hz, 1000 Hz, 2000 Hz, 4000 Hz, and 8000 Hz) were measured with a sound level meter (Bruel & Kjaer 2230) and the set up used for the measurements was as follows:

- Ref. - Test - Operate : Operate
- FSD : 80 (110) dB
- Reset : All
- Frequency Weighting : A

- Ext. Filter : In (to make frequency measurements) / Out
- Sound Incidence : Random
- Display : SPL
- Time Weighting : Fast
- Detector : RMS.

A band- pass filter set (Bruel & Kjaer 1612) with 1/3 - 1/1 octave filter set (Bruel & Kjaer 1625) was used to measure the outputs for the necessary frequencies. The set up for theses instruments are as follows:

- Input Switch : Direct
- Weighting Network : Off
- Function Selector : 1/3 Octave 0 dB
- Automatic Switching : Off
- External Battery : Off
- Frequencies used (Hz) : 63 / 125 / 250 / 500 / 1000 / 2000 / 3000 / 4000 / 8000 / White Noise
- Step Size- Bandwidth : 1/3 Oct. 1/1 Oct.
- Recording Speed : Fast

An integration and filter control module (Bruel & Kjaer ZR 0035) was used with a printer (Bruel & Kjaer 2318) to print the results. The set up for this instrument was as follows:

- Measurement Period : 1 Min.
- Mode : Operate (start printing)
  Reset (stop printing and measuring)
- SLM Type - SLM Range : 2230 20-90 dB
- Filter : Off

<u>Method</u>:

To prevent, as much as possible, the effect of background noise, measurements in the selected concert hall were taken at night, when the concert hall and the surrounding spaces were totally empty. The main floor and the first floor balcony were the places where measurements are conducted.

To decrease the number of seats to be measured and to use the limited time efficiently, the acoustical symmetricity of the hall were tested. Two symmetrical seats in the same row , and five different rows in the whole space were investigated for this procedure. Measured sound pressure levels show that the space is almost acoustically symmetrical (Table 5.1).

Forty five seats in the main floor and twelve seats in the balcony floor were chosen to collect the data for the evaluation (Fig 5.5). The second floor balcony was not measured as it is designed for purposes other than seating.

The sound source was placed in the middle of the stage, to the closest point to the first row of the hall. The microphone was placed on each seat during the measurement. Sound pressure levels for eight different frequencies (63 Hz, 125 Hz, 250 Hz, 500 Hz, 1000 Hz, 2000 Hz, 4000 Hz, and 8000 Hz), and white noise were measured with the sound level meter. Only Leq., maximum, and minimum sound pressure levels were collected for the study. The collected data during the measurements are given in the following tables. Table 5.2 shows the data collected at the main floor of the concert hall. Second floor (main balcony) measurements are given in the Table, 5.3.. Data, collected from the measurements for the analysis of white noise are summarized in Table 5.4..

koro-A1	Leq	max.	min.	koro-A2	Leq	max.	min.
63 Hz	37.3	43	0	63 Hz	37.6	43.5	31.1
125 Hz	44	49.1	0	125 Hz	42.6	47	38.3
250 Hz	57.7	61.5	0	250 Hz	57.8	62.3	53.9
500 Hz	67.6	71	64.4	500 Hz	68.3	71	65.4
1000 Hz	72.2	74.3	70	1000 Hz	71.3	73.1	69.2
2000 Hz	68.6	72.6	54	2000 Hz	69	71	67.3
4000 Hz	63.6	64.9	62.6	4000 Hz	64.7	65.9	63.7
8000 Hz	49.2	50.1	48.3	8000 Hz	48.5	50.6	47.6
W. N.	56.7	57.5	56	W. N.	56.2	56.9	55.5

bal- G9	Leq	max.	min.	bal-G10	Leq	max.	min.
63 Hz	31	37.2	0	63 Hz	30.2	34.9	0
125 Hz	42.8	47.5	36.8	125 Hz	41.5	46	34.5
250 Hz	59.7	64.3	55.7	250 Hz	60.6	65.7	55.8
500 Hz	67.4	70.1	64	500 Hz	69.6	72.9	67
1000 Hz	70.8	72.7	68.5	1000 Hz	71	73.1	68.9
2000 Hz	71.5	73.3	70.1	2000 Hz	71.6	73.7	70.1
4000 Hz	66.5	67.6	65.2	4000 Hz	66.7	67.9	65.3
8000 Hz	50.5	51.9	49.6	8000 Hz	50.1	52.6	49.1
W. N.	58	61	57.4	W. N.	58.1	59.6	57.6

O21	Leq	max.	min.	O20	Leq	max.	min.
63 Hz	35.3	40.3	0	63 Hz	35.2	40.6	0
125 Hz	42.8	48.6	0	125 Hz	43.2	49.8	36.7
250 Hz	55.7	59.7	41.6	250 Hz	57.6	62.2	0
500 Hz	67	70.4	41.6	500 Hz	66.8	70.5	41.4
1000 Hz	72.3	74.6	43.8	1000 Hz	71.8	74	62
2000 Hz	72.1	73.9	62.4	2000 Hz	72.3	73.8	69.6
4000 Hz	74	75.3	72.5	4000 Hz	73.8	75	71.3
8000 Hz	57.9	59.1	56.9	8000 Hz	55.9	56.9	52.5
W. N.	62	79.1	59.8	W. N.	61.5	65.7	61.1

J3	Leq	max.	min.	J4	Leq	max.	min.
63 Hz	34.2	40.7	0	63 Hz	32.8	39.9	0
125 Hz	43.6	48.8	38.4	125 Hz	44.4	49.1	38.2
250 Hz	60.1	64.6	0	250 Hz	57.8	62.1	53.7
500 Hz	68.4	71.1	65.6	500 Hz	68.6	71.5	65.5
1000 Hz	71.6	73.7	69.5	1000 Hz	72.8	74.8	70.5
2000 Hz	70.1	71.8	68.2	2000 Hz	70.9	72.6	53.2
4000 Hz	66.1	67.3	64.9	4000 Hz	67.2	68.4	66.2
8000 Hz	51.5	52.5	50.6	8000 Hz	53.1	54.1	52.2
W. N.	56.9	57.5	56.3	W. N.	58.1	62.7	57.4

C17	Leq	max.	min.	C16	Leq	max.	min.
63 Hz	41.6	47.3	35.1	63 Hz	40.8	46.2	34.8
125 Hz	47.2	50.7	42.8	125 Hz	47.1	51.5	41.9
250 Hz	61.4	65.4	57.9	250 Hz	61.8	65.7	57
500 Hz	71.6	74.2	68.9	500 Hz	73	75.8	69.9
1000 Hz	76.6	78.6	74.9	1000 Hz	77.2	79.8	75.2
2000 Hz	76.5	77.7	75	2000 Hz	74.4	75.9	72.7
4000 Hz	71.9	72.9	70.7	4000 Hz	70.7	72.2	69.7
8000 Hz	54.6	56.5	53.7	8000 Hz	59.7	60.8	58.8
W. N.	63.1	82	40	W. N.	61.7	62.5	61.1

Table 5.1 : Sound pressure levels in dB measured to test the symmetrical distribution of the sound in the concert hall. The word, 'koro' refers to the seats reserved for the chorus, 'bal' refers to the balcony floor, and the indication given by a letter and a numerical (A2) describes the location of seat by its row (A) and seat (2).

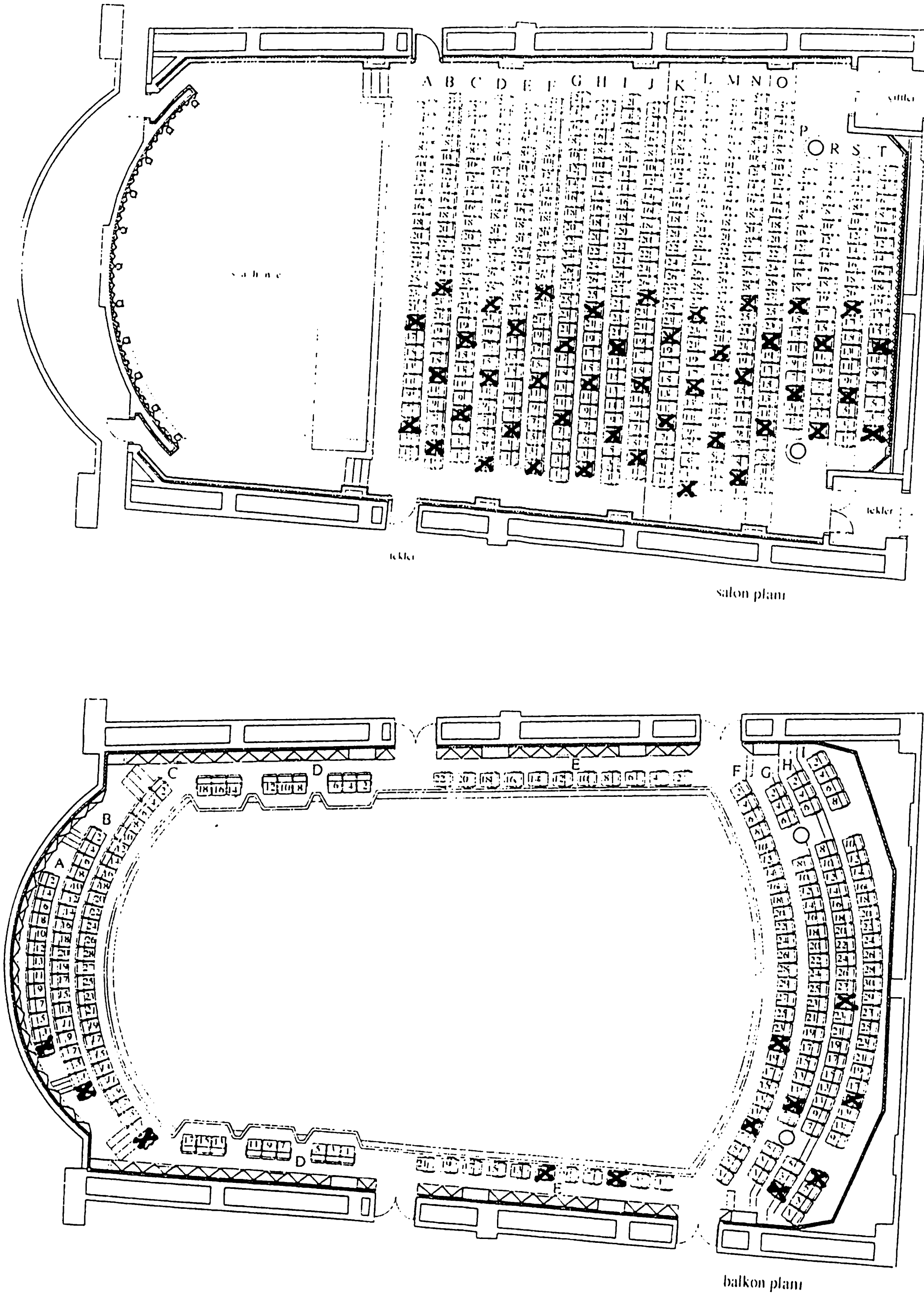


Figure 5.1 : The presentation of seats used in the main floor and in the first floor balcony to collect data.

63 Hz	Leq	max.	min.
A5	36.6	41.9	0
A19	43.6	49.3	36.9
B3	38	44.3	31.4
B13	39	44.9	30.5
B25	44.7	50	37.2
C7	39.9	45	33.2
C17	41.7	49.2	35.6
D1	32.9	38.1	0
D13	38.4	44.7	32.3
D23	42.5	48.5	34
E5	38.9	45.2	31.2
E19	40	46.7	32.7
F1	32.1	37.3	0
F13	37.7	43.3	30.3
F25	40	45	33.3
G9	37.1	42.3	30.5
G19	37.5	44.7	30.1
H1	32.3	37.4	0
H13	38.1	44.1	30.1
H23	38.6	43.8	30.8
I7	31.6	35.9	0
I19	36.9	42.7	30.7
J3	34.2	40.7	0
J13	36.8	41.4	0
J25	39.4	46.2	0
K9	33.9	39.6	0
K21	34.9	39.7	0
L1	39.3	44.6	0
L15	38.6	44.7	31
L25	36.3	41.8	0
M7	36.6	43.9	0
M19	36.3	41.6	0
N3	34.9	40.5	0
N17	36.8	42.8	0
N27	34.4	40.8	0
O9	30.4	34.5	0
O21	35.3	40.3	0
P5	33.3	38.3	0
P17	37.3	42.5	31.1
R1	32.7	37.7	0
R13	35.4	40.1	0
S7	31	37.4	0
S19	30.4	34.8	0
T1	35.2	41.3	0
T13	35.6	51.9	0

125 Hz	Leq	max.	min.
A5	47.6	53.7	42.1
A19	50.3	55.7	44.2
B3	44.8	48.9	38.5
B13	47.6	52	42.7
B25	52.4	56.4	47.8
C7	47.6	51.8	42.6
C17	48.7	54.5	44.5
D1	47.3	51.9	42.5
D13	44.5	49.9	39
D23	45.6	50.7	40.7
E5	42.5	47.4	0
E19	43.3	47.7	38.7
F1	45.9	50	39.5
F13	44.1	48.5	39.1
F25	45	50.7	39
G9	41.7	47.2	36.8
G19	41.3	47.6	34.1
H1	42.3	47.1	37.8
H13	42.8	49.1	38
H23	43.1	47.3	35.5
I7	43.1	47.1	38.7
I19	41.2	45.4	36.6
J3	43.6	48.8	38.4
J13	42.4	47.2	36.2
J25	45	50.9	39.8
K9	43.5	48.7	0
K21	42.1	47.1	36.9
L1	41.8	47.2	36.5
L15	40.2	45.3	0
L25	41.1	46.3	0
M7	36.7	47	31.8
M19	39.8	47.2	0
N3	41.8	47.5	35.4
N17	43.3	48.1	37.5
N27	40.8	46.3	0
O9	40.2	52.9	33.9
O21	42.8	48.6	0
P5	41.8	46.3	0
P17	41.2	47.2	0
R1	38.3	43.7	32.4
R13	39	45	33.4
S7	36.3	40.9	0
S19	37.4	41.7	31.6
T1	39.1	43.9	0
T13	43.6	48.9	0

Table 5.2.: Print out of the data collected for the analysis of sound pressure level distribution of eight different frequencies at the main floor of the concert hall during the measurements

Table 5.2. (*cont'd*).

250 Hz	Leq	max.	min.
A5	62.6	66.4	58.8
A19	70.9	75.3	65.2
B3	61.2	65.6	57.4
B13	61.2	65.1	56.8
B25	67	70.5	63.2
C7	60.1	63.6	55.9
C17	61.4	64.6	57.4
D1	57.2	61.7	53
D13	60.2	63.9	56
D23	63.2	66.9	59.5
E5	58.1	62	53.8
E19	61	65.2	55.3
F1	57	60.3	53.3
F13	58.5	62.7	54.2
F25	63	67.4	57.8
G9	59.7	63.5	55.8
G19	59	65.7	0
H1	58.8	62.3	55
H13	59.7	63.7	55
H23	60.8	64.9	0
I7	58	62.7	53.7
I19	60.4	64.2	0
J3	60.1	64.6	0
J13	59.1	63	55.2
J25	59.5	63.3	55.4
K9	61.1	65.4	56.2
K21	59.2	62.7	56.1
L1	56.3	60.1	51.7
L15	59.6	63.7	30.9
L25	58	61.8	34.7
M7	58.3	61.2	53.7
M19	57.2	61.1	44.3
N3	57.5	61.1	40.4
N17	58.1	62.7	46.1
N27	59.2	63.9	55.1
O9	57.2	60.3	0
O21	55.7	59.7	41.6
P5	56.8	60	37.3
P17	56	59.8	36.6
R1	55.2	59.8	50.7
R13	52.9	56.9	48.6
S7	57.9	64.1	0
S19	55.8	60.6	51.3
T1	53.3	57	0
T13	55	59.1	30.7

500 Hz	Leq	max.	min.
A5	71.9	74.8	68.9
A19	76.7	79.6	73.8
B3	70	72.9	66.6
B13	72.8	75.3	70.2
B25	73.9	76.6	71.4
C7	69.7	72.7	67
C17	71.2	74.2	68.7
D1	69.9	72.6	66.3
D13	71.1	74.3	67.9
D23	71.5	74.2	68.7
E5	69.7	73.1	66.7
E19	70.7	73.2	67.3
F1	69	71.8	64.9
F13	69.9	73.1	67.3
F25	70.2	73.3	67
G9	68.7	71.2	65.8
G19	69.9	72.9	39.7
H1	67.6	71.3	38.2
H13	69.7	72.7	66.6
H23	69.8	72.5	66.9
I7	67.8	71.3	64.9
I19	70.1	73.1	66.8
J3	68.4	71.1	65.6
J13	68.9	72.6	65.5
J25	69.6	72.3	66.4
K9	68.3	71.2	41.7
K21	69.4	72.1	66.2
L1	67.2	72.8	40.1
L15	68.5	71.5	43.5
L25	67.3	70.2	46.3
M7	66.5	69.4	63.8
M19	68.4	71.2	40.3
N3	66.3	69.1	46.3
N17	66.2	69	63.6
N27	67.9	70.8	64.8
O9	65.3	68.4	37.5
O21	67	70.4	41.6
P5	65.8	69	39.3
P17	66.7	69.5	64.2
R1	64.7	68.4	60.5
R13	65.9	69.1	62.5
S7	63.3	66.5	37.3
S19	64.7	67.6	61.8
T1	64.8	67.6	62
T13	62.6	65.5	36.4

Table 5.2 (*cont'd*).

1000Hz	Leq	max.	min.	**2000Hz**	Leq	max.	min.
A5	73.6	75.9	70.9	A5	69.3	71.1	67.3
A19	78.6	80.5	76.7	A19	78.7	80.3	77.1
B3	72.8	75	70.1	B3	69.5	71.3	67.6
B13	72.4	74.1	70.6	B13	71.1	72.4	69.6
B25	78.9	80.9	76.7	B25	84.5	86.2	83
C7	71.4	73.2	69.4	C7	69.1	70.7	67.3
C17	75.1	77.1	73.2	C17	76.3	78	74.6
D1	72.5	74.7	70.5	D1	68.9	70.8	67.2
D13	74.6	76.7	72.8	D13	73.1	74.9	71.6
D23	76.7	78.6	75	D23	78.9	80.4	77.6
E5	72.8	74.9	70.7	E5	70	71.6	68.5
E19	75	77.2	72.8	E19	75.4	76.9	74.1
F1	73.1	75.1	70.8	F1	69.8	71.7	68
F13	72.8	74.9	70.6	F13	72.2	73.9	70.5
F25	75.7	78	73.8	F25	76.2	77.9	74.7
G9	72.3	74.5	49.9	G9	70.8	72.6	69
G19	71.9	75.2	49	G19	73.1	75.1	72
H1	72.8	74.8	70.3	H1	69	71	67.3
H13	72.6	75.5	50	H13	71.5	72.9	69.9
H23	73.5	75.5	71.5	H23	73.1	74.7	53
I7	70.9	72.8	68.9	I7	70	71.6	68.3
I19	72	74.3	70.2	I19	71.7	73.2	70.1
J3	71.6	73.7	69.5	J3	70.1	71.8	68.2
J13	72.6	74.7	70.6	J13	70.9	72.5	58.8
J25	73.6	76.2	71.3	J25	72.4	73.7	70.9
K9	71.6	73.9	44.8	K9	70.9	72.5	69.3
K21	72.5	74.8	70.5	K21	72.1	74	70.7
L1	72	73.9	62.1	L1	70.5	72.5	66.2
L15	72.8	74.9	70.3	L15	71.7	73.8	46.9
L25	72.3	74.5	51.9	L25	72.6	74.2	48.3
M7	71.7	74.1	58.7	M7	71.2	72.9	69.7
M19	73.3	75.3	71.3	M19	71.9	74.1	45
N3	71.4	73.7	45.1	N3	71.2	72.6	69.8
N17	72.3	74.3	70.4	N17	72.5	74.4	71
N27	73.6	76.1	51.7	N27	72.8	74.4	71.4
O9	71.9	74.4	55.5	O9	70.5	72.1	47.6
O21	72.3	74.6	43.8	O21	72.1	73.9	62.4
P5	70.9	73.3	48.7	P5	71.3	72.8	70
P17	73.4	76.1	71	P17	71.3	73.6	69.8
R1	70.8	72.9	68.6	R1	70.7	72.2	68.9
R13	72.1	74.1	70	R13	71.8	73.5	61.7
S7	71.4	74.4	32.8	S7	71.2	72.9	44.9
S19	72	74.2	69.8	S19	73.1	75.9	64.8
T1	71.7	73.8	69.6	T1	71.7	73.3	54.1
T13	72.6	75.2	45.5	T13	71.8	74.4	47.8

Table 5.2 (*cont'd*).

4000Hz	Leq	max.	min.	**8000Hz**	Leq	max.	min.
A5	66.6	68	65.4	A5	50.7	51.6	49.9
A19	71.5	72.7	70.3	A19	63.9	65.1	63
B3	65	66.6	48.4	B3	50.3	52.4	48.5
B13	67.6	68.6	66.3	B13	56.1	56.9	55.3
B25	83	84	82.1	B25	75.9	76.7	75.2
C7	65.5	66.6	64.3	C7	54.6	55.6	53.6
C17	68.6	69.8	67.6	C17	54.9	56	53.9
D1	66.1	67.4	64.9	D1	53.6	54.4	52.7
D13	68	69.2	66.7	D13	55.1	56.1	54.3
D23	80.6	81.7	79.8	D23	70	70.7	69.3
E5	65.6	66.7	64.5	E5	55.7	56.8	54.7
E19	76.3	77.4	75.2	E19	65.6	66.5	64.9
F1	65.2	66.3	64.1	F1	54.2	55.3	53.4
F13	67.6	68.7	66.4	F13	51.9	52.7	51.1
F25	78.6	79.6	77.6	F25	70.1	70.9	69.1
G9	66.8	68.2	65.7	G9	52	52.9	51
G19	73.3	74.8	72.2	G19	63.3	64.4	52.8
H1	65.9	67.2	48.9	H1	53.5	54.6	52.6
H13	68.5	69.5	67.3	H13	56.7	57.7	55.9
H23	75.1	76.3	74	H23	66.9	68.6	54.6
I7	66.2	67.3	65.1	I7	50.9	52.1	50.2
I19	71.4	73.3	50.9	I19	62.6	63.7	61.7
J3	66.1	67.3	64.9	J3	51.5	52.5	50.6
J13	68.9	69.9	67.7	J13	57.9	58.9	57
J25	74.1	75.1	73	J25	66.6	67.6	65.8
K9	67.4	68.4	66.1	K9	54.2	55.1	53.4
K21	73.6	74.9	72.6	K21	63.7	64.8	62.9
L1	66.3	67.5	65	L1	49.8	50.7	48.8
L15	70.9	72	53.8	L15	59.5	71.7	35.2
L25	74.5	75.8	48.5	L25	63.1	67.3	43
M7	68	69.3	66.7	M7	52.6	53.5	51.7
M19	73.7	75	72.3	M19	60.3	61.9	41.4
N3	67.7	68.9	66.5	N3	50.7	52.3	31.5
N17	73.1	74.3	71.8	N17	55.6	56.8	31.3
N27	75.6	76.7	74.4	N27	62.4	76.2	39.9
O9	69.9	72.4	41.8	O9	55.9	70.6	35
O21	74	75.3	72.5	O21	57.9	59.1	56.9
P5	72	73.3	70.9	P5	56.5	57.6	31
P17	74.6	75.6	73.5	P17	60.5	61.6	59.3
R1	70.3	71.4	69.2	R1	55	56.1	53.9
R13	73.8	75.1	72.6	R13	55.9	57.1	54.7
S7	72.3	74	46.3	S7	54.5	55.6	53.4
S19	74.7	75.9	73.7	S19	56.9	58.2	55.7
T1	70.7	73.1	54.1	T1	55.7	56.9	54.4
T13	73.7	75	56.9	T13	57.9	59	32.3

63 Hz	Leq	max	min.
bal-F9	0	32.9	0
bal-F21	30.8	37.9	0
bal-G9	31	37.2	0
bal-H1	0	30.1	0
bal-H25	32.5	38	0
bal-I 7	30.7	35.7	0
bal- I 15	31.9	38.6	0
kenar 5	34.6	40.6	0
kenar 11	0	32.6	0
koro-C1	30.4	35	0
koro-B1	37.1	41.9	30.9
koro-A1	37.3	43	0

125 Hz	Leq	max.	min.
bal-F9	39.3	44	34.2
bal-F21	39.6	44.2	0
bal-G9	42.8	47.5	36.8
bal-H1	39.1	43.9	34.4
bal-H25	44.4	49.3	39.3
bal-I 7	39.3	45	33.9
bal- I 15	44.3	49.3	0
kenar 5	39.7	44.1	35
kenar 11	41.7	45.4	36.1
koro-C1	41.4	45.3	35.4
koro-B1	41.6	46.8	35.5
koro-A1	44	49.1	0

250 Hz	Leq	max.	min.
bal-F9	58.4	63.2	54.6
bal-F21	58.5	62.1	53.9
bal-G9	59.7	64.3	55.7
bal-H1	56.3	60.1	52
bal-H25	60.5	64.4	53.9
bal-I 7	57.8	62.2	52.6
bal- I 15	56.4	60.1	52.4
kenar 5	60.1	63.9	55.9
kenar 11	59.4	63.6	55.3
koro-C1	57.4	61.9	52.8
koro-B1	57.9	64	53.3
koro-A1	57.7	61.5	0

500 Hz	Leq	max.	min.
bal-F9	68	70.4	65.5
bal-F21	69	72.1	66.2
bal-G9	67.4	70.1	64
bal-H1	68.1	71.4	64.8
bal-H25	68.9	72.4	65.1
bal-I 7	66.3	70	63
bal- I 15	66.7	69.4	63.1
kenar 5	68.3	71.2	65.8
kenar 11	69.9	73.2	66.7
koro-C1	69	72.2	66.2
koro-B1	66.9	69.9	63.7
koro-A1	67.6	71	64.4

1000Hz	Leq	max.	min.
bal-F9	71.4	73.2	69.2
bal-F21	72.2	74.5	69.8
bal-G9	70.8	72.7	68.5
bal-H1	70.9	73	68.9
bal-H25	73	75.5	70.7
bal-I 7	71.5	73.6	69.6
bal- I 15	72.4	74.5	69.7
kenar 5	71.6	73.5	69.6
kenar 11	71.4	74	69.2
koro-C1	72	74.2	69.7
koro-B1	72.1	75.1	70
koro-A1	72.2	74.3	70

2000Hz	Leq	max.	min.
bal-F9	70.2	72	68.7
bal-F21	71.3	72.8	69.9
bal-G9	71.5	73.3	70.1
bal-H1	69.4	71.1	43.9
bal-H25	72.1	74	70.2
bal-I 7	68.9	70.7	67
bal- I 15	72.5	74.4	71.1
kenar 5	68.1	69.8	66.4
kenar 11	67.4	68.8	65.7
koro-C1	68.4	70	66.7
koro-B1	68.4	70.4	51.6
koro-A1	68.6	72.6	54

4000Hz	Leq	max.	min.
bal-F9	64.5	65.8	63.5
bal-F21	67.3	68.7	46.9
bal-G9	66.5	67.6	65.2
bal-H1	63.7	65.3	62.7
bal-H25	69.2	70.5	68
bal-I 7	64.5	65.9	63.3
bal- I 15	66.9	68	65.7
kenar 5	63.1	64.2	62
kenar 11	63	64.2	61.9
koro-C1	63.6	64.9	62.4
koro-B1	65.9	67.4	64.4
koro-A1	63.6	64.9	62.6

8000Hz	Leq	max.	min.
bal-F9	47.2	48	46.4
bal-F21	52	52.9	51.2
bal-G9	50.5	51.9	49.6
bal-H1	47.6	48.9	46.7
bal-H25	53.6	54.4	52.8
bal-I 7	46.9	47.8	45.9
bal- I 15	50.8	56.3	49.8
kenar 5	51	51.9	50.1
kenar 11	49.5	50.4	48.7
koro-C1	50.5	52.5	49.5
koro-B1	53.9	55.3	52.8
koro-A1	49.2	50.1	48.3

Table 5.3. : Print out of the data collected for the analysis of distribution of sound pressure levels of eight different frequencies at the balcony floor of the concert hall during the measurements.

W. N.	Leq	max.	min.
A19	64.5	65.2	63.8
B13	58.7	59.3	57.6
C7	57	61.7	54
D1	57.4	59.4	56.5
F25	66.6	72.8	66.1
G19	62.6	73.6	61.7
H13	58.9	63.1	58.2
I 7	56.9	58.5	55.9
J3	56.9	57.5	56.3
J25	62.5	63.2	62.1
K21	62	67.3	61.4
L15	60	61.5	57.2
M7	58.3	60	55.1
N3	60.8	84.3	43.2
O21	62	79.1	59.8
P5	59.9	61.6	59.2
R1	59	62.1	58.5
S19	61.4	62.4	56.7
T13	61.3	62.7	60.7
bal-F9	56.8	63.9	56.2
bal-F21	58.4	60.3	57.8
bal-G9	58	61	57.4
bal-H1	56	57.5	55.3
bal-H25	58.7	65.4	58.1
bal-I 7	55.9	60.3	55.2
bal- I 15	58.3	64.8	57.6
kenar 5	55.8	56.6	55.3
kenar 11	55.6	56.6	55.1
koro-C1	56.4	60.4	55.8
koro-B1	56.7	64.1	55.8
koro-A1	56.7	57.5	56

Table 5.4 : Print out of the data collected for the analysis of white noise distribution in the whole concert hall during the measurements .

Measurements, for the analysis of white noise at the main floor of the concert hall, were taken only in the selected seats to make a general evaluation for the distribution of sound in the space, rather than studying the individual conditions for each seat.

Also, to make comparisons for how much sound is lost in the space, sound pressure level in front of the random noise generator has measured by placing the microphone just in front of the sound source and the results of the test are printed (Table 5.5).

TEST	Leq	max.	min.
63 Hz	81.3	85.5	73.8
125 Hz	88.6	92.7	61.7
250 Hz	94.2	98.7	64.5
500 Hz	102.8 ^	103.6 ^	78.7
1000 Hz	103.5 ^	103.9 ^	102.7 ^
2000 Hz	102.5 ^	103.2 ^	101.6 ^
4000 Hz	102.0 ^	103.8 ^	98.7
8000 Hz	94.4	101.2 ^	72.7
W. N.	95.5	98.9	82.3

Table 5.5: Sound pressure levels in front of the sound source. ('^' sign expresses the overloading of sound pressure level to the sound level meter)

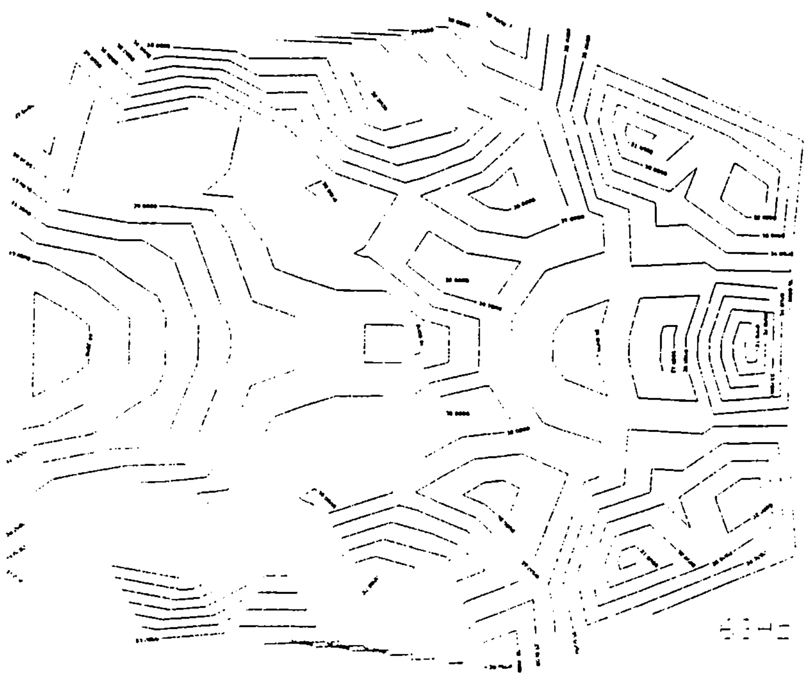
5.3 EVALUATION OF THE COLLECTED DATA FROM THE MEASUREMENTS IN BILKENT CONCERT HALL

5.3.1 EVALUATION OF THE DATA OF THE MAIN FLOOR

63 HERTZ : The measured sound pressure level just in front of the source is 81.3 dB. As the distance between the source and the first row of the concert hall is 2 meters, a 12 dB drop in the sound pressure level is supposed to be achieved at the first row of the hall referring to the section 2.3 of the second chapter. When it is calculated, an output of 69.3 dB sound pressure level is expected without any reinforcement of reflections coming from the surfaces of the room. But the actual measured sound

pressure level for this row is 44 dB, and this fact shows that there is a great attenuation at 63 Hz sound. Similar results are obtained until one reaches the 'G' row. The reinforcement of sound by the reflections is clearly seen, especially after the 'G' row. The distribution of 63 Hz frequency sound over the audience seating area of the main floor of the concert hall is given in Figure 5.6. A decrease is seen towards the side walls of the first few rows. The reason for this can be the random noise generator, which produces directional sound. Because of this reason, it can be assumed that, in the real performances, the seats closer to the side walls can receive more sound than it is measured.

The highest obtained sound pressure level is 44 dB, and the lowest one is 30 dB in the space, that refers to an average of 37 dB. According to the measurements for the 63 Hz sound, the first 3 or 4 rows of the room receives more bass sound than the side, and back rows of the hall. The areas shown on the Figure 5.7. receive less levels of bass sound compared to the other seats in the hall. Although the last row of the main floor is the farthest point to the sound source, it receives better sound energy than some areas of the space. The reason can be the reflections from the rear wall of the concert hall which highly reinforce the sound coming to the last rows.



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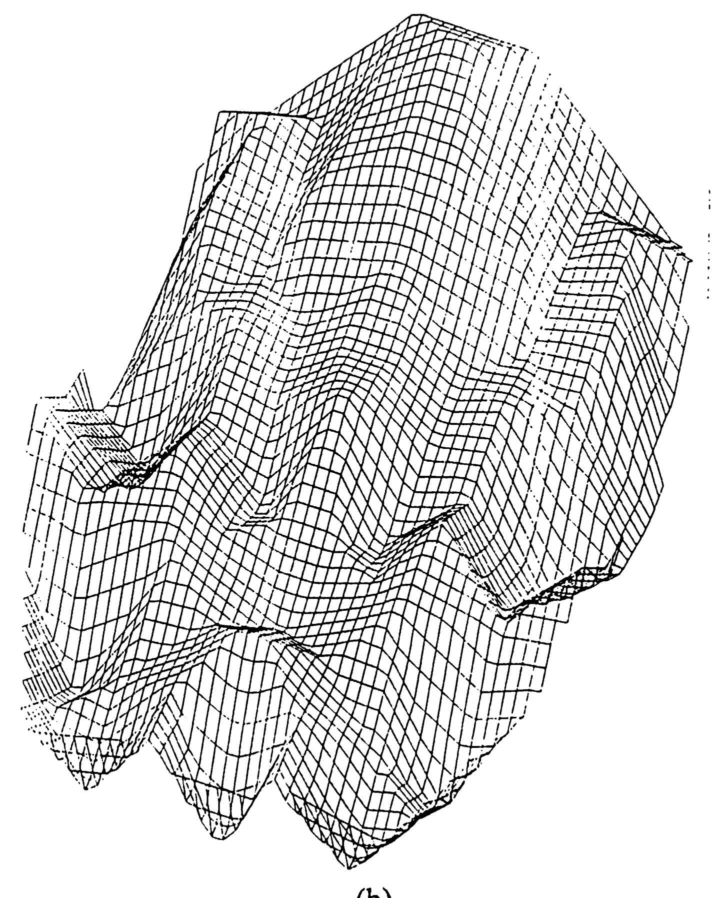

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Figure 5.6. : (a) Distribution of 63 Hz low frequency sound over the audience seating area. (b) Three dimensional presentation of the distribution of 63 Hz frequency sound in the hall.

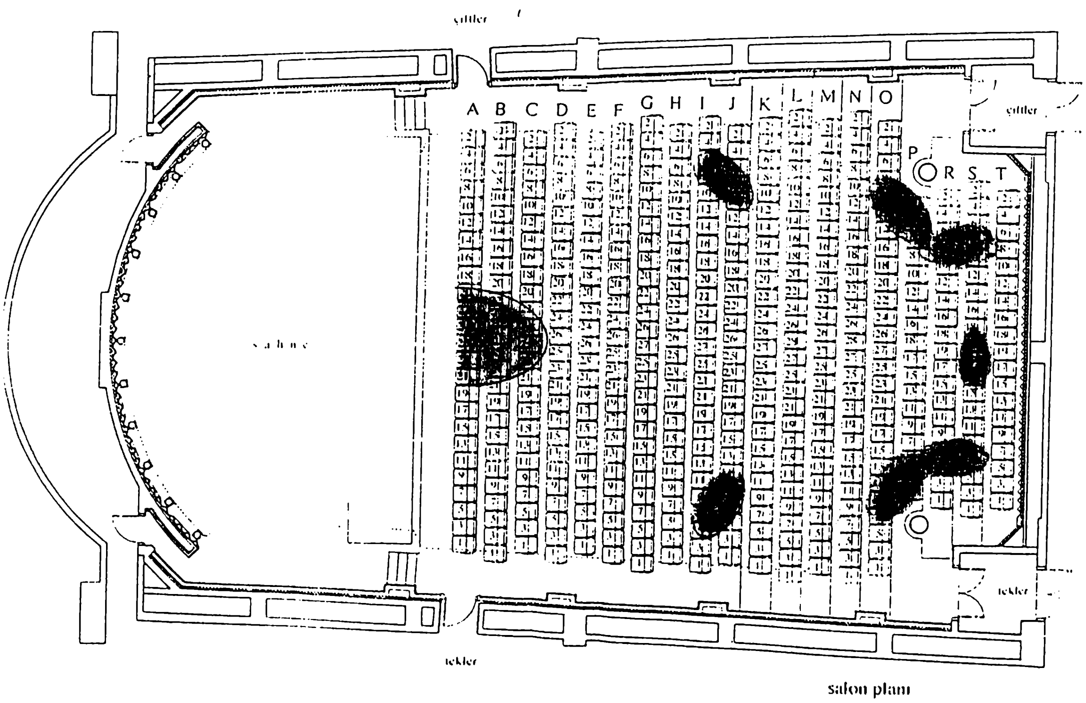
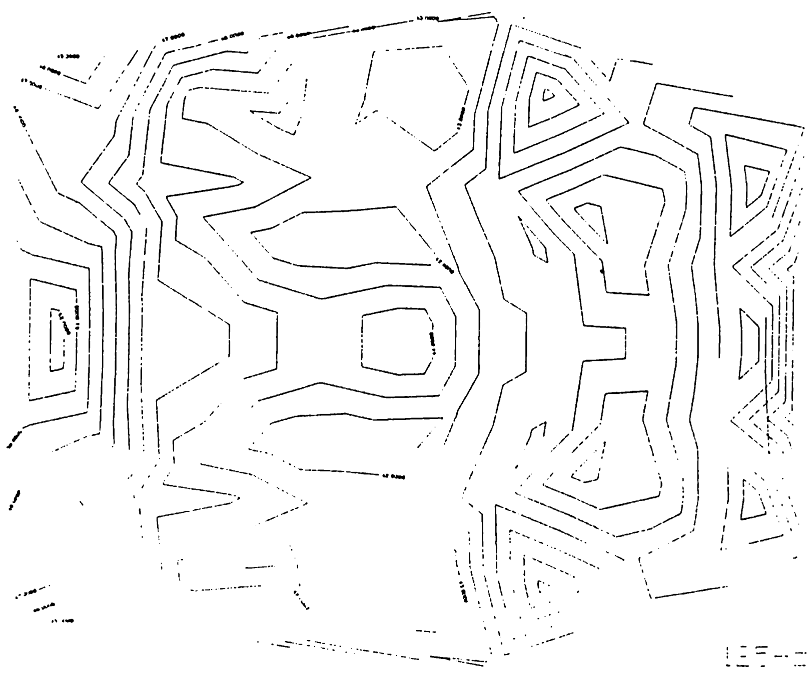


Figure 5.7. : Indication of the seats that receive the highest (green area) and the lowest (red area) sound pressure levels of 63 Hz frequency sound

<u>125 HERTZ</u> : The measured sound pressure level just in front of the source is 88.6 dB. If the distance is doubled twice to the first row of the room, the sound intensity is supposed to be 76.6 dB with a drop of 12 dB. But the measured sound level for 125 Hz frequency sound for the first row is 52 dB, lower than it is supposed to be. Towards the I -row the expected level of sound is achieved in the hall with the help of reflections coming from the vertical and horizontal surfaces. The distribution of sound pressure levels is given in Figure 5.8.. It can be seen that there is high reinforcement in the hall for the 125 Hz frequency sound. The amount of reinforcement changes between 20 dB and 75 dB. The layout given in Fig, 5.8. shows a decrease towards the side walls for the first 3 or 4 rows, but this reduction is again may be related to the directional loud speaker used in the noise generator. So the



(a)

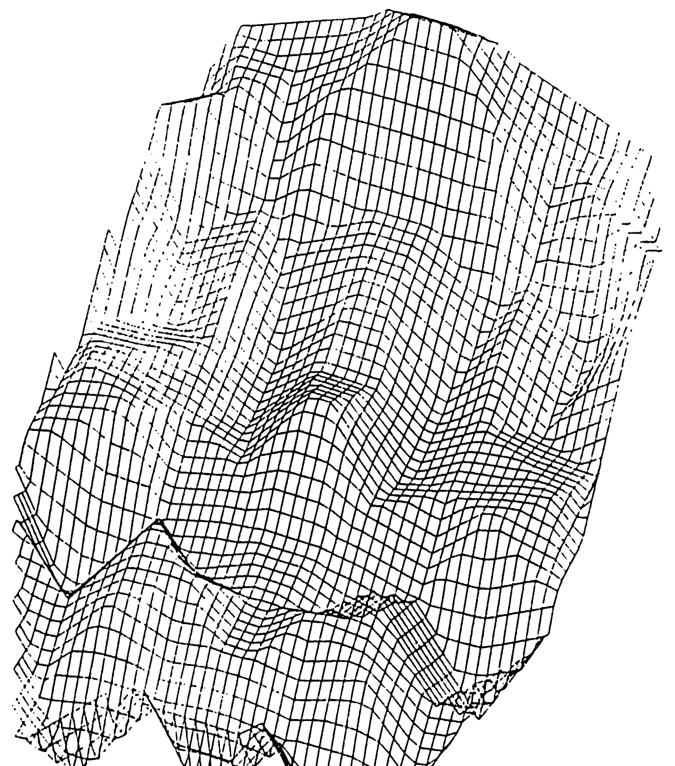


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Figure 5.8.: (a) Distribution of 125 Hz trequency sound over the audience seating area. (b) Three dimensional presentation of the distribution of 125 Hz frequency sound in the hall

measured values obtained for these seats should be higher than the ones indicated in the layout.

The highest measured sound pressure level is 52 dB, and the lowest is about 36 dB. The average sound pressure level is around 44 dB in the concert hall. The rows closer to the stage receives higher intensity levels of 125 Hz sound than the remaining part of the room. On the other hand, there are locations on the sides, closer to the back wall, and around 'M', 'N', 'O' rows which are acoustically poor, and receives less sound intensity of 125 Hz sound (Figure 5.9.). Sound is so reinforced by the reflections at the last row that it has about 6 -7 dB more than the hall average. Same is valid for the seats placed in the center of 'S' and 'R' row.

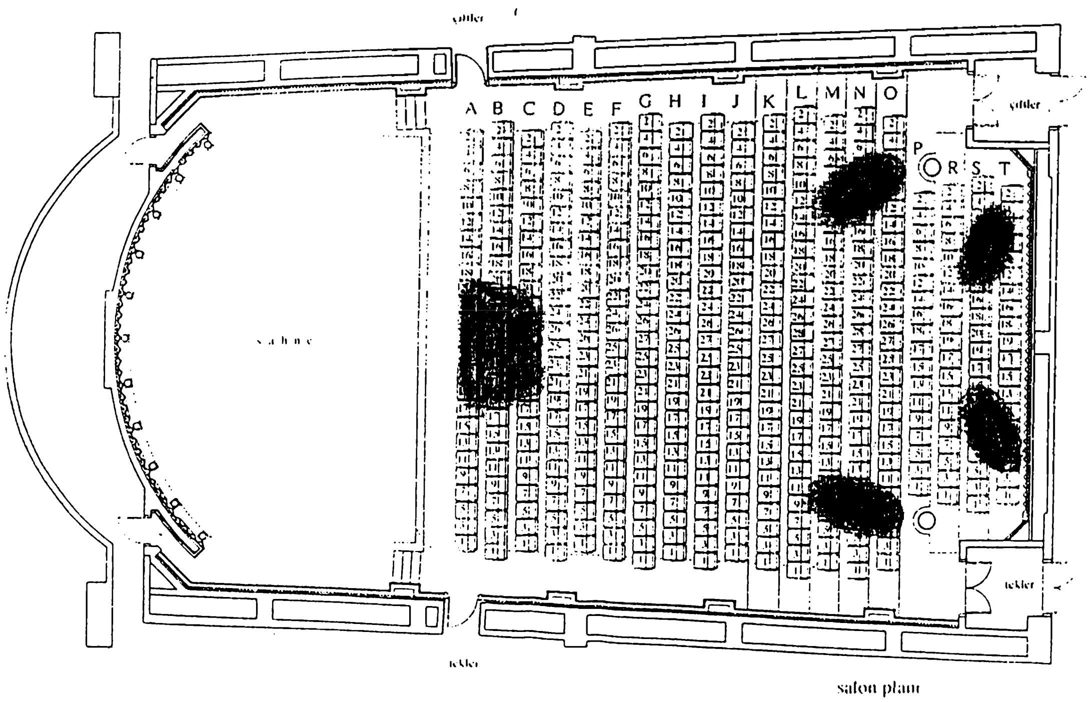
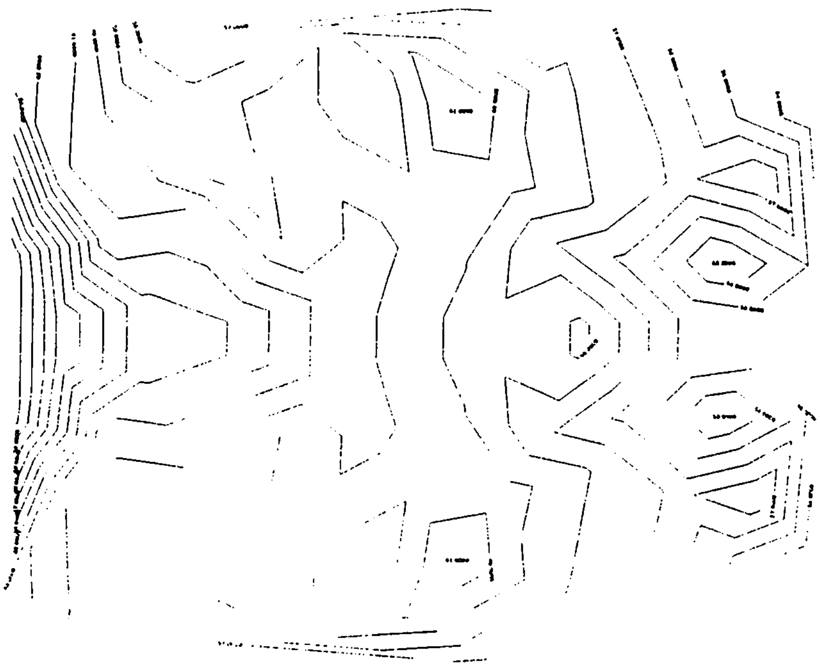


Figure 5.9.: Indication of the seats that receive the highest (green area) and the lowest (red area) sound pressure levels of 125 Hz frequency sound

250 HERTZ: The measured sound pressure level for testing the 250 Hz frequency sound is around 94 dB and the sound pressure level at the first row is 70 dB. Although the expected sound pressure level at the first row, which is 2 meters away the sound source, is 82 dB, the actual measured value is only 70 dB and it is 12 dB less than the expected level at the first row. The distribution and attenuation of 250 Hz frequency sound in the space is fairly uniform (Figure 5.10.). The reinforcement of direct sound with the help of reflections coming from the boundaries of the concert hall is clearly seen as the measured values are higher than the expected values referring to Figure 2.8. 90 dB is the maximum and 4 dB is the minimum reinforcement values obtained from the measurements. Seats placed at the sides of 'K', 'L', 'M' rows receive great amount of reflected sound from the side walls and from the ceiling that the measured sound pressure levels are higher than the most of the seats in the hall. Again, the seats towards the side wall at the first few rows seem to have lower values than the seats placed in the middle of the same row, but the reason again may be the directionality of the sound source used during the measurements.

The highest measured sound pressure level is 70 dB, and the lowest one is 52 dB. The average is around 61 dB in the hall. These results show that, there are no great intensity level variations in the whole space. Some seats achieve the sound better or worse than others (Figure 5.11.), but for the 250 Hz frequency sound, there is a chance for all seats to receive nearly equal amount of sound with the help of



(a)

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Figure 5.10.: (a) Distribution of 250 Hz frequency sound over the audience seating area. (b) Three dimensional presentation of the distribution of 250 Hz frequency sound in the hall.

reflections coming from the boundaries of the enclosure and these reflections reinforce the direct sound to be perceived as a strong signal for the listener.

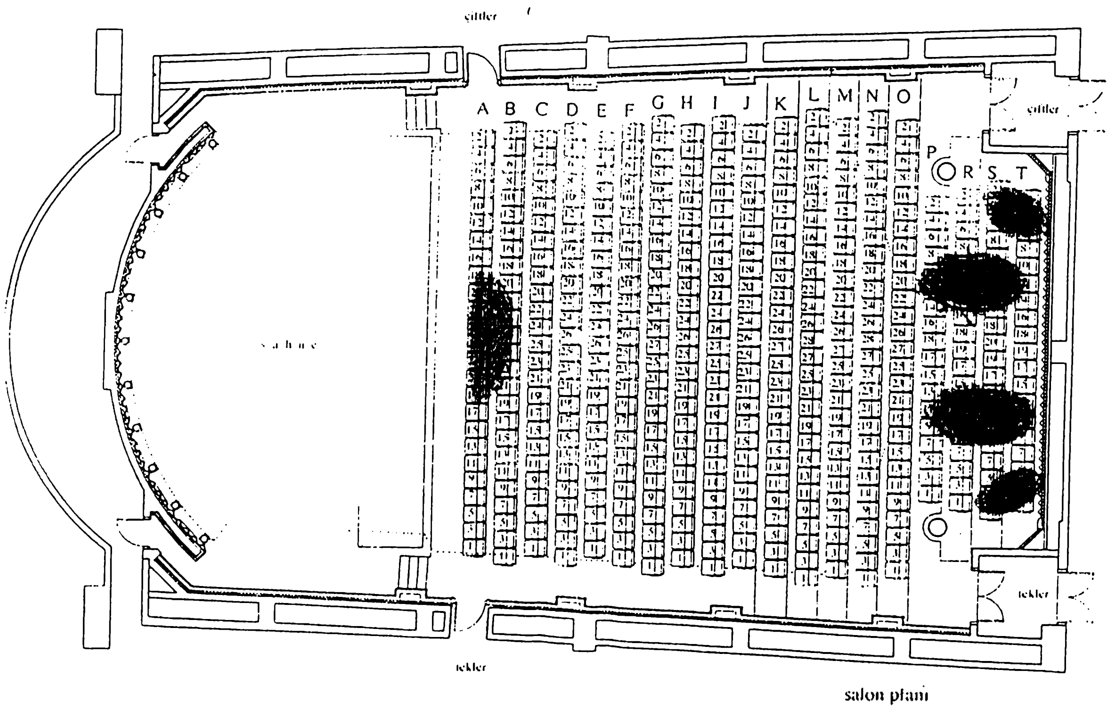
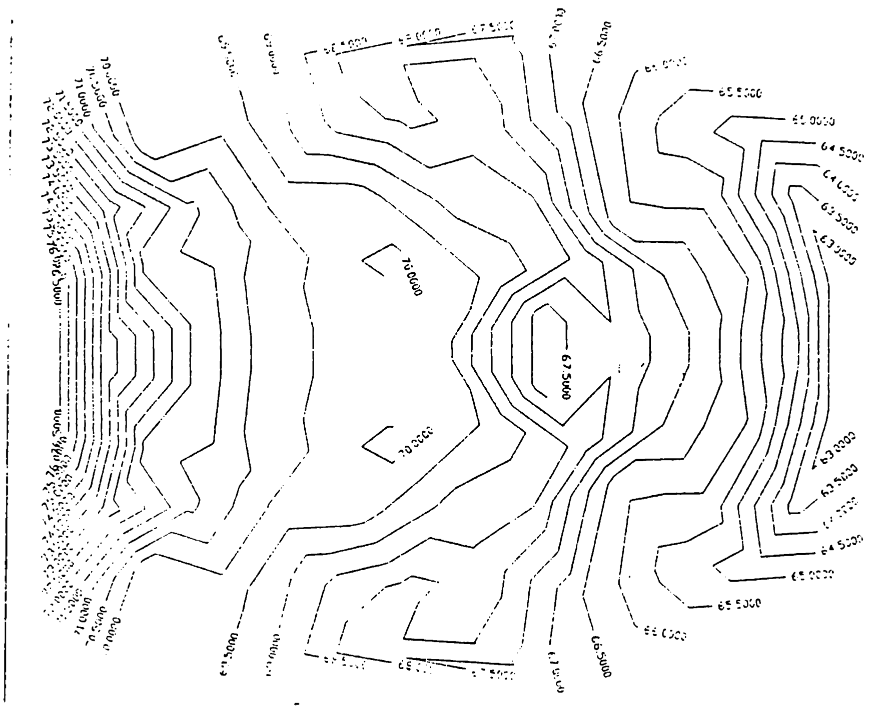


Figure 5.11. : Indication of the seats that receive the highest (green area) and the lowest (red area) sound pressure levels of 250 Hz frequency sound

<u>500 HERTZ</u> : 102.8 dB was measured just in front of the sound source and 90.8 dB is the expected value for the first row of the concert hall. But the result obtained after the measurements is only 76 dB for the first row as it was for the other frequencies analyzed before. After the first three rows, the expected sound pressure levels are achieved and there is smooth attenuation pattern for the 500 Hz frequency sound (Figure 5.12.).



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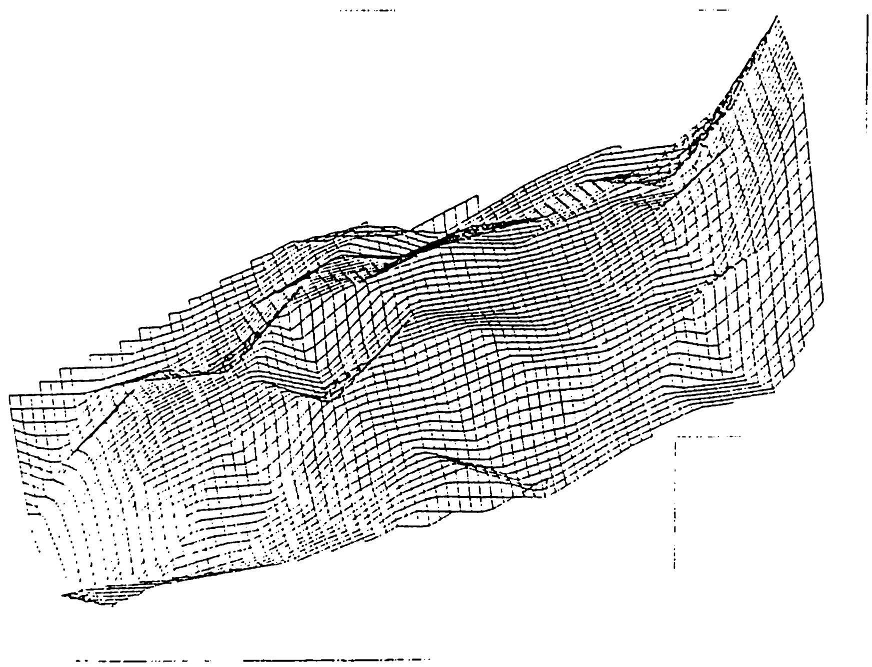

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Figure 5.12.: (a) Distribution of 500 Hz frequency sound over the audience seating area. (b) Three dimensional presentation of the distribution of 500 Hz frequency sound in the hall.

There is the value of 76 dB for the highest measured sound pressure level, and there is the 62 dB for the lowest measured value. 69 dB is the average sound pressure value for the concert hall, which is obtained from the measurements of 500 Hz frequency sound. The highest and the lowest values measured in the space are so close to the average value that, equal distribution of sound all over the space can be talked. The reinforcement of sound with the help of reflections vary from 4 dB to 80 dB. On the contrary to the other frequencies studied before, the last row of the main floor receives the lowest sound pressure level among the other seating areas (figure 5.13). The reason may be the absorption of the wall material at 500 Hz frequency sound more than other frequencies. Measurements show that, the hall is successful in distributing the 500 Hz frequency sound equal to every area of the concert hall.

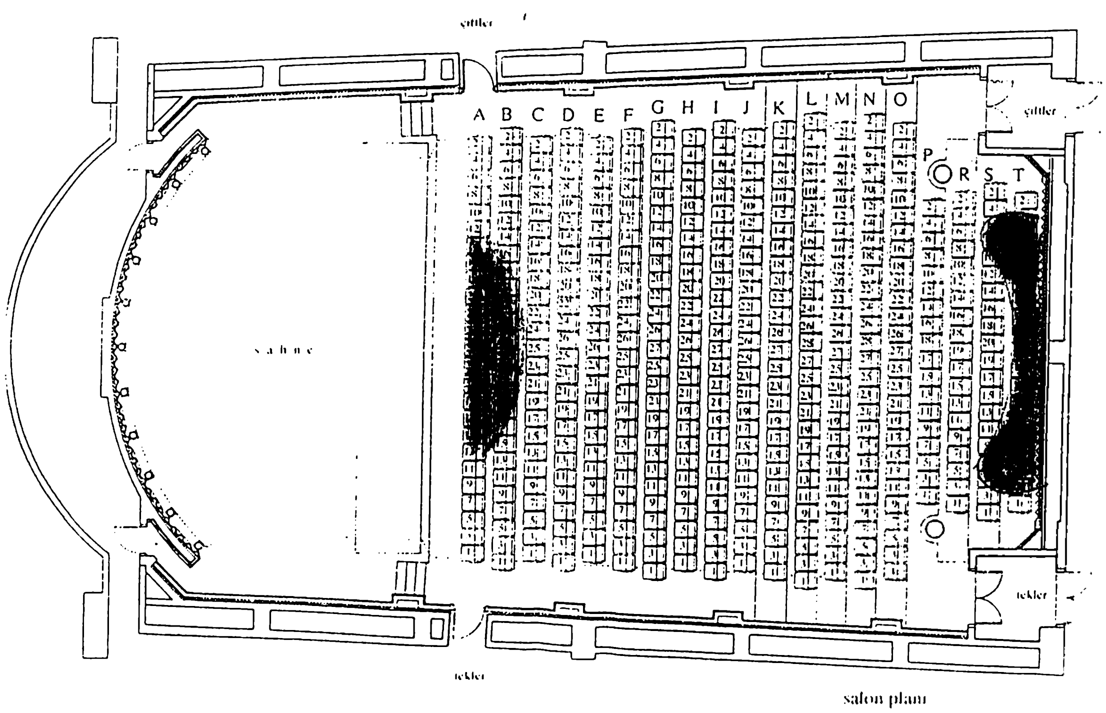
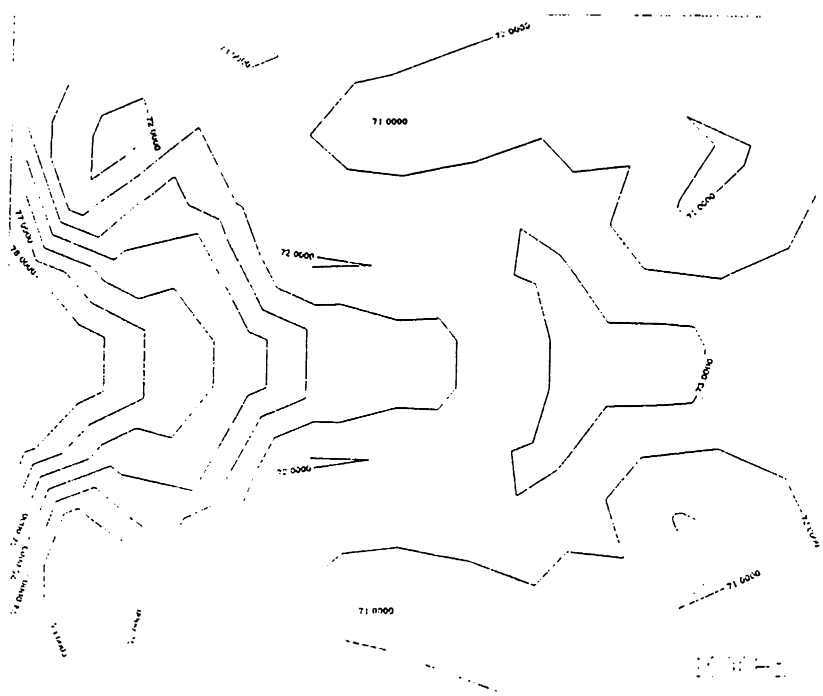


Figure 5.13. : Indication of the best (green area) and the worst (red area) locations by means of receiving 500 Hz sound .

1000 HERTZ : When the pressure level distribution of 1000 Hz frequency sound (Figure 5.14) is studied, it is seen that, there are no excessive intensity level variations between different seating areas. The maximum level measured is 78 dB and the minimum value measured during the investigations is 70 dB. There is only an 8 dB difference between the seat that receives most sound energy and the seat that receives least. Treatment of 1000 Hz frequency sound in the concert hall is more successful than the frequencies studied before, and it is clearly seen from the figure 5.14.. On the other hand, the measured sound pressure level just in front of the sound source is about 103.5 dB. There is again a great amount of attenuation of sound until it reaches to the first row of the concert hall.

Reinforcement of the direct sound in the hall is clearly seen as the last row of the concert hall receives nearly equal amount of sound pressure levels of the rows closer to the stage. The seats placed at the first 3 or 4 rows of the hall receive higher levels of sound than the seats placed in the remaining areas of the concert hall. The seats at the sides of the rows from 'H' to 'T' receive 1000 Hz frequency sound less than the rest of the hall (Figure 5.15). Although the seats, achieving less sound pressure levels, seem to cover a large area in Figure 5.15., this would not cause any differences in the perception of music as the variance between the highest and the lowest measured sound intensity level is only 8 dB in the whole space. The concentration of the seats, having higher intensity levels, in the center of the hall depends on the directional sound generated from the random noise generator. The seats adjacent to these ones may receive higher values of sound pressure levels, if the sound source used during the study was not directional.



(a)

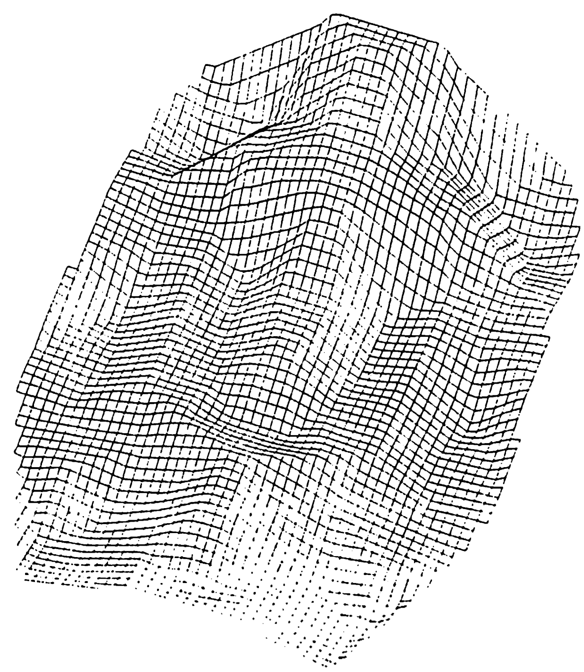


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Figure 5.14. : (a) Distribution of 1000 Hz frequency sound over the audience seating area. (b) Three dimensional presentation of the distribution of 1000 Hz frequency sound in the hall

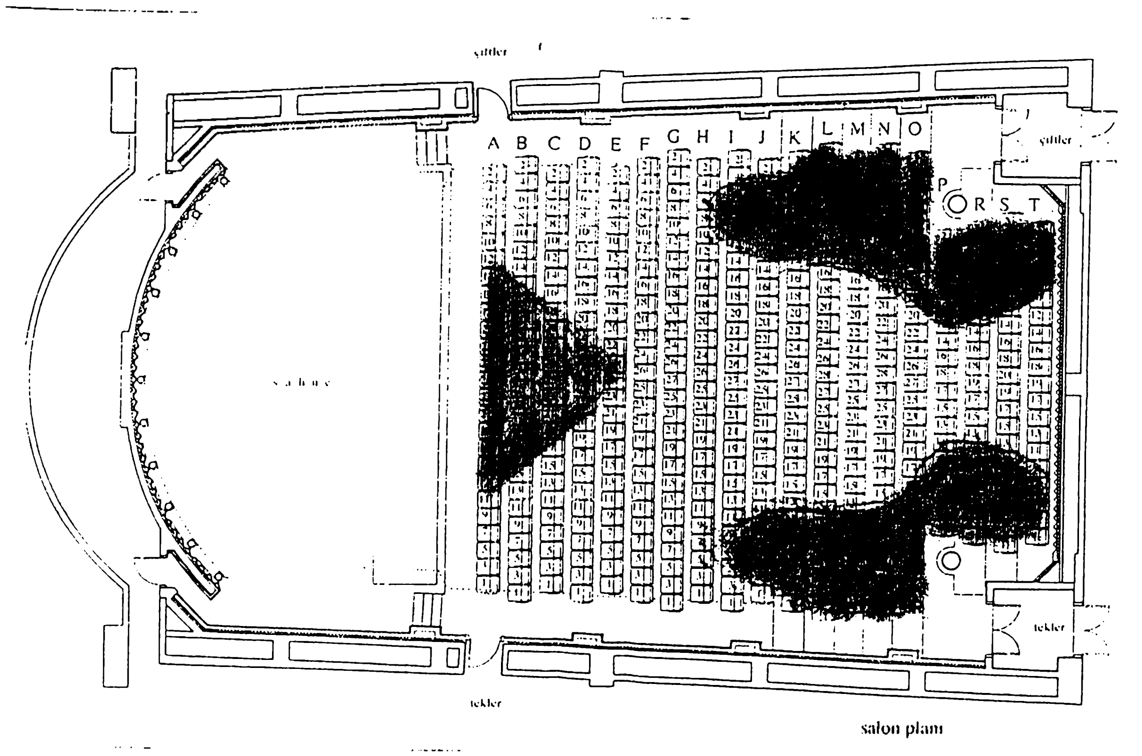
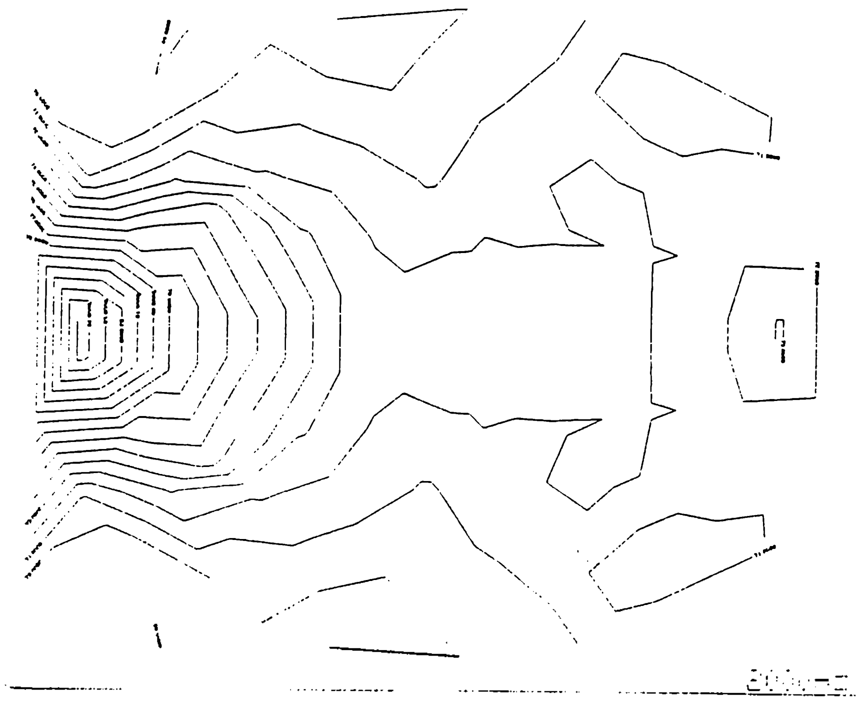


Figure 5.15. : Indication of the seats that receive the highest (green area) and the lowest (red area) sound pressure levels of 1000 Hz frequency sound

<u>2000 HERTZ</u> : The sound pressure level distribution layout of 2000 Hz frequency sound, over the audience area, is a little bit different than the layout obtained for the frequencies between 63 Hz and 1000 Hz.(Figure 5.16.). When the previous frequency ranges were studied, it was seen that, the first row of the hall always received the highest sound intensity level. In 2000 Hz frequency sound, the second, third and the forth rows receive more sound energy than the first row. The reason may be the reinforcement of direct sound over this area more than the rest of the hall.



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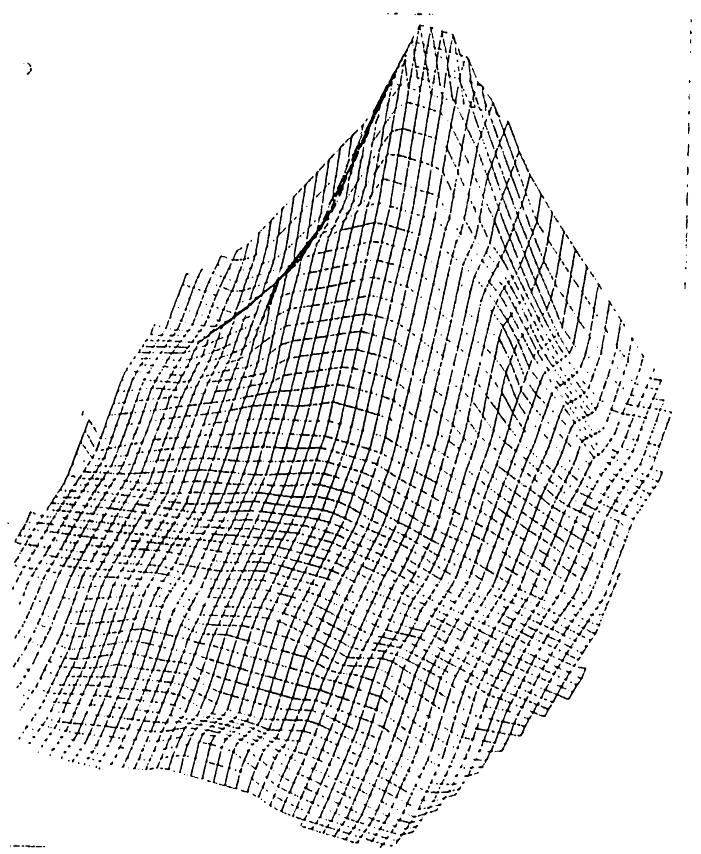

(b)

Figure 5.16. : (a) Distribution of 2000 Hz frequency sound over the audience seating area. (b) Three dimensional presentation of the distribution of 2000 Hz frequency sound in the hall

The maximum measured sound level is 84 dB and the minimum one is 68 dB in the hall, which means an average of 76 dB. A 102.5 dB sound pressure level was measured just in front of the sound source, and referring to Figure 2.8 the estimated level for the first row is around 90 dB. As there is only a difference of 6 dB between what is expected and what was obtained for the first rows, there is no unusual attenuation of sound in the hall for the first 2 meters, as it was seen for the other frequencies.

The layout of the seats receiving less sound energy in the space, is wider than the areas obtained for the other frequencies studied (Figure 5.17.). The seats located

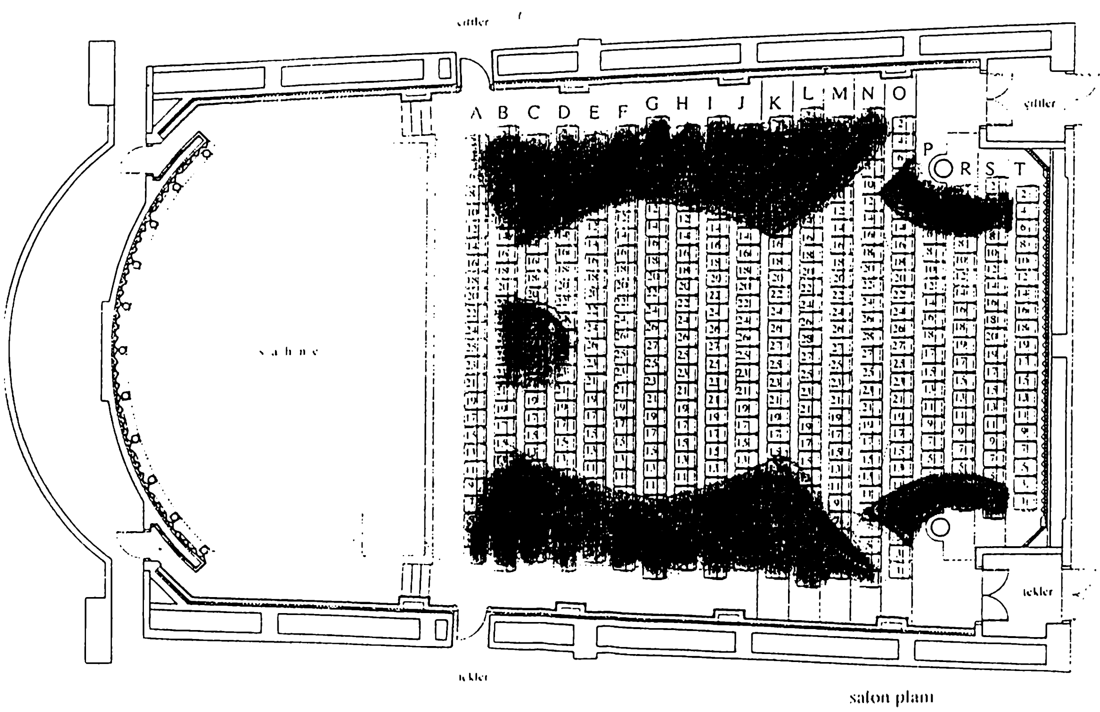

Figure 5.17. : Indication of the seats that receive the highest (green area) and the lowest (red area) sound pressure levels of 2000 Hz frequency sound

closer to the walls, receive 2000 Hz frequency sound energy least. The reason may be the absorption of this frequency sound by the enclosures of the concert hall or by the upholstered seats.

<u>4000 HERTZ</u> : The maximum measured sound pressure level for 4000Hz frequency sound is around 80 dB and the minimum one in the hall is about 65 dB. A clear drop of sound intensity level through the side walls is seen in the space (Figure 5.18). The reinforcement of direct sound is distinct over the third, and forth rows. The measured level of sound at these rows are higher than the ones measured at the first row of the concert hall. Also the estimated value (90 dB) for the first row has little difference with the measured one (82 dB), and this shows the great attenuation of sound is again eliminated for this frequency range.

The best seats for the 4000 Hz frequency sound are the ones in the center of the rows from 'B' to 'E'. The seats which have less sound intensity levels are the ones placed closer to the side walls (Figure 5.19.). These seats are the same ones having less sound pressure levels for the 2000 Hz frequency sound. The absorption of high frequency sound can be speculated referring to the data obtained from the measurements. The last rows of the concert hall receive higher levels of sound pressure than some areas of the hall, although there is great distance between them and the stage. The attenuation of direct sound because of distance is eliminated for these rows with the help of the reflections which reinforce the 4000 Hz frequency sound.

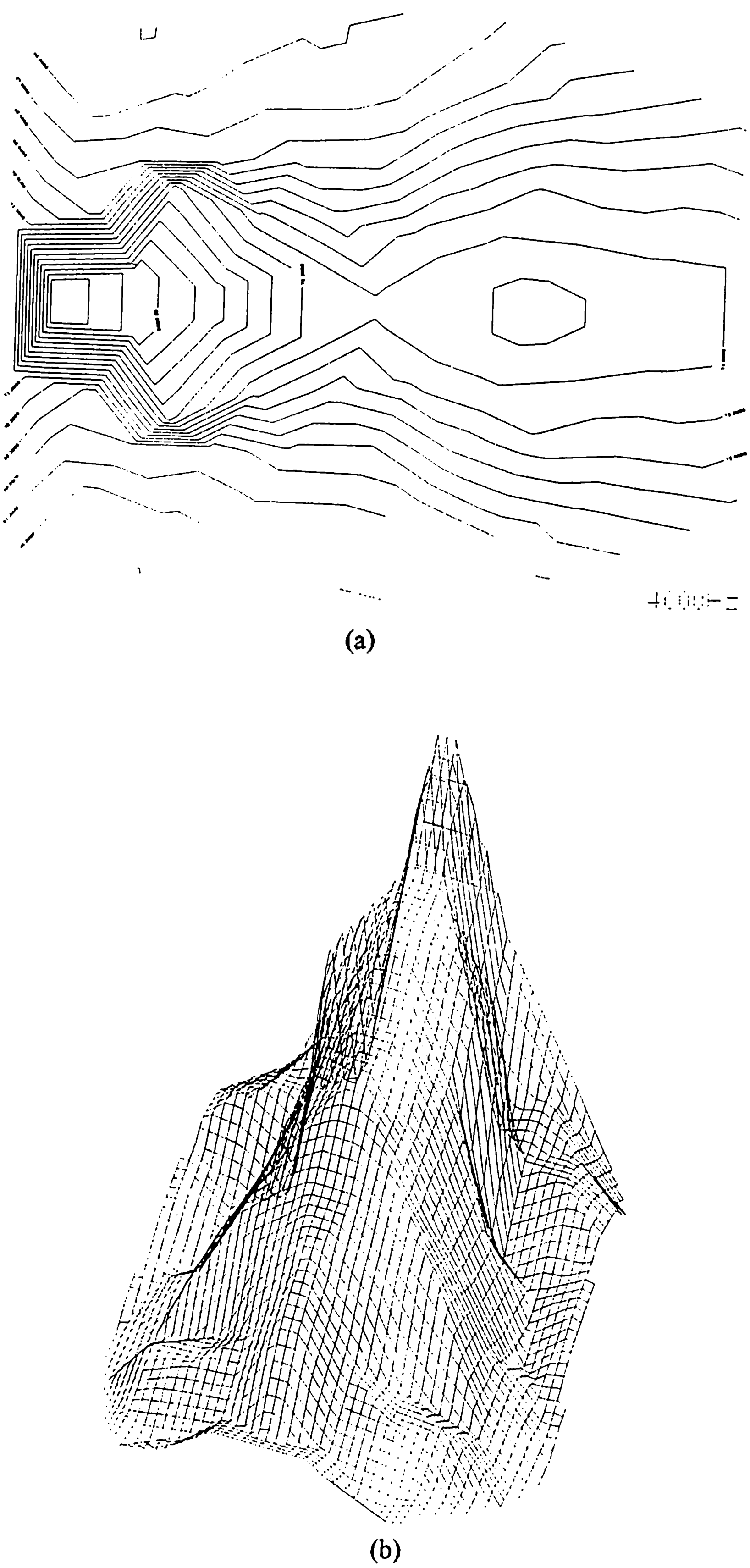

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Figure 5.18. : (a) Distribution of 4000 Hz frequency sound over the audience seating area. (b) Three dimensional presentation of the distribution of 4000 Hz frequency sound in the hall

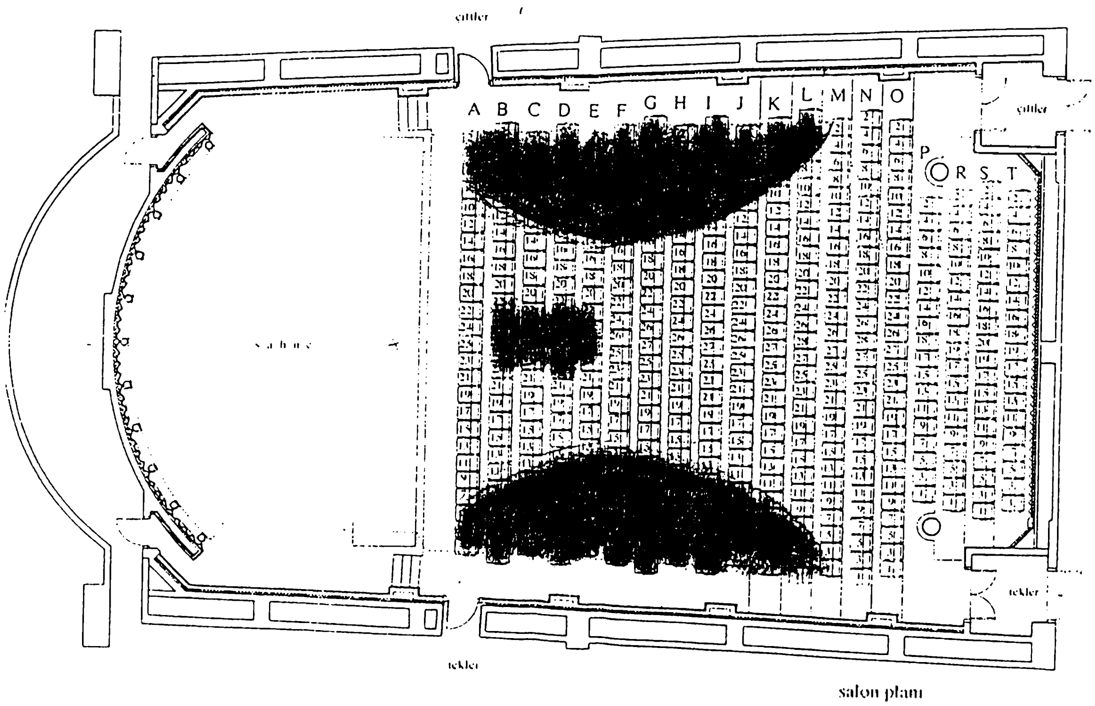
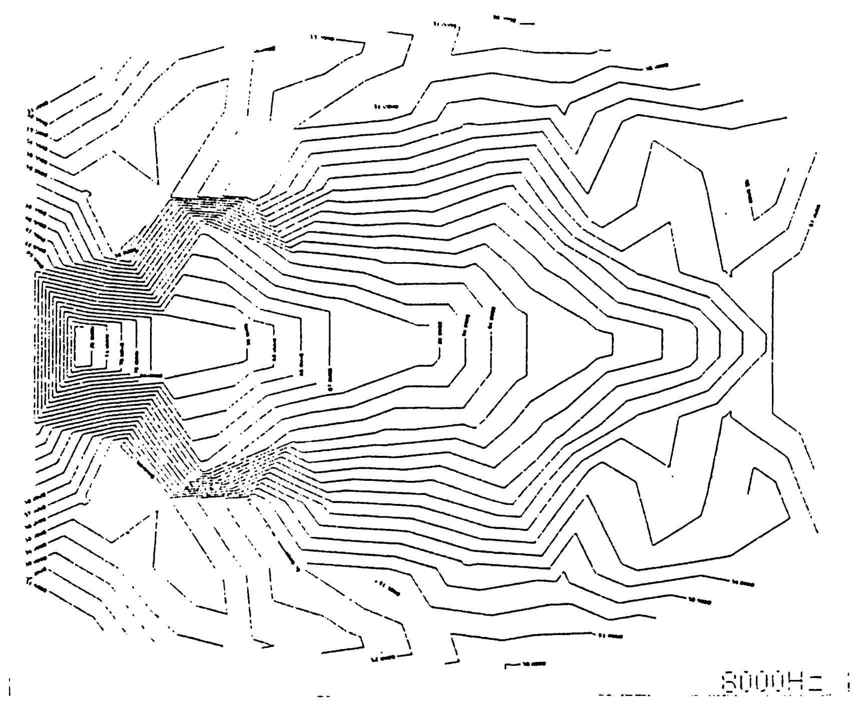


Figure 5.19. : Indication of the seats that receive the highest (green area) and the lowest (red area) sound pressure levels of 4000 Hz frequency sound

<u>8000 HERTZ</u> : Among the four high frequency sounds (1000, 2000, 4000, 8000); the 8000 Hz frequency one has the lowest measured sound pressure level during the case study. Although the data obtained from the test measurement is around 102 dB and nearly same with the ones obtained for the other high frequency sounds, the maximum intensity level achieved for the seating area is 75 dB and the minimum value is about 50 dB. The total distribution of 8000 Hz frequency sound in the concert hall is given in Figure 5.20.. It can be summarized that there is a decrease in the sound intensity level towards the back, and towards the sides of the concert hall.

The effect of the reinforcement of the reflected sound on the direct sound is mostly achieved at the center of the 'B' and 'C' rows. Also, the data obtained from the last



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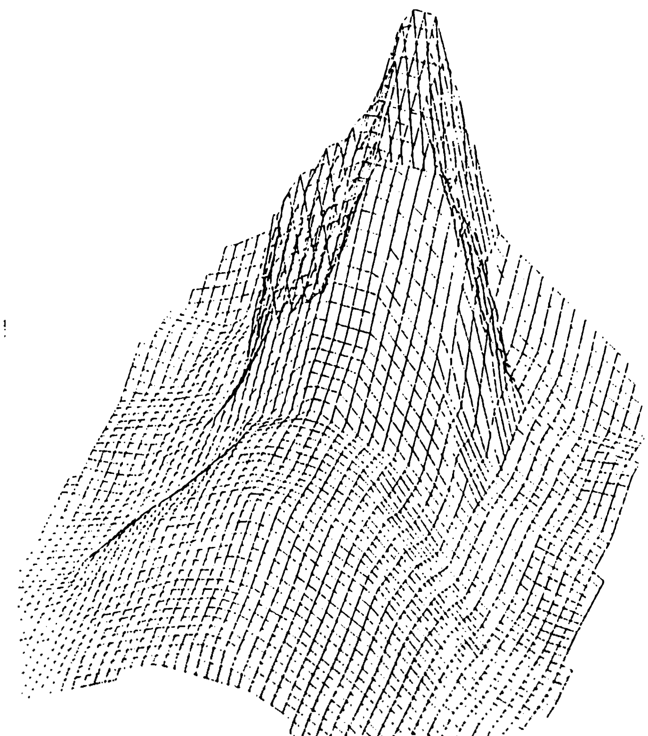

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Figure 5.20. : (a) Distribution of 8000 Hz frequency sound over the audience seating area. (b) Three dimensional presentation of the distribution of 8000 Hz frequency sound in the hall

row of the concert hall shows the effect of reflection from the rear wall on the reinforcement of direct sound. An output of 57 dB is measured for the last row and this output is 7 dB more than the minimum measured level in the hall. So the loss of sound depending on the distance is eliminated by the help of rear wall reflections for the far seating areas.

There are of course seats acoustically better than the others when 8000 Hz frequency sound is considered. The rows beginning from 'G' and goes up to 'O' receive lesser sound intensity levels at the seats near the side walls (Figure 5.21).

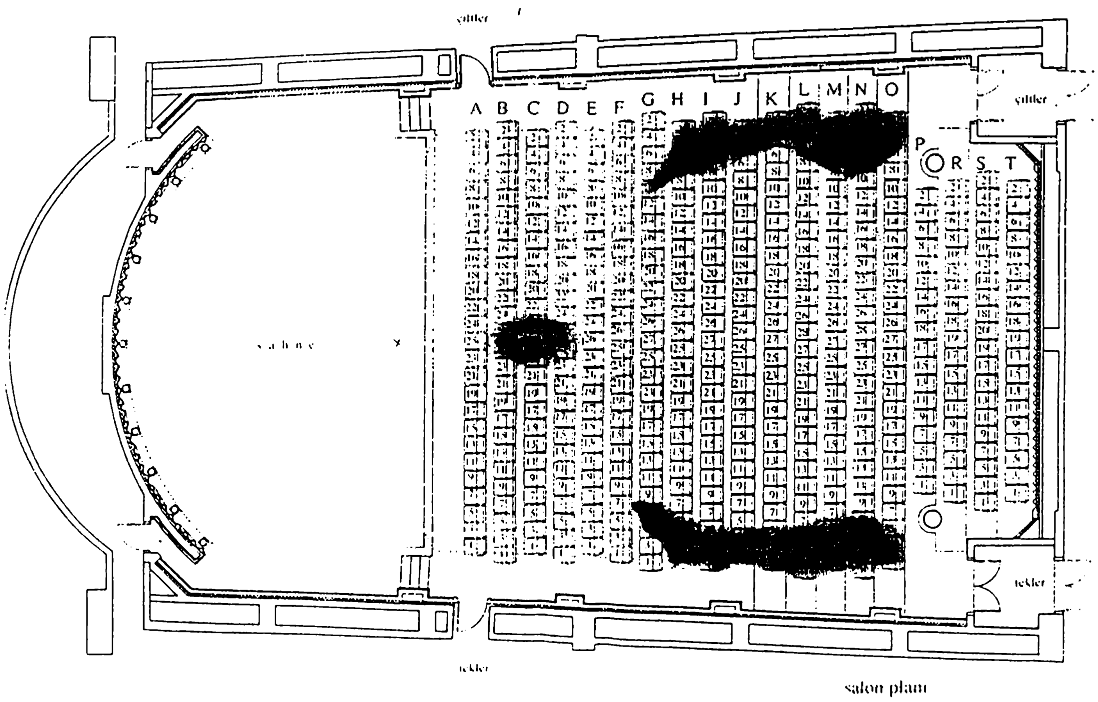
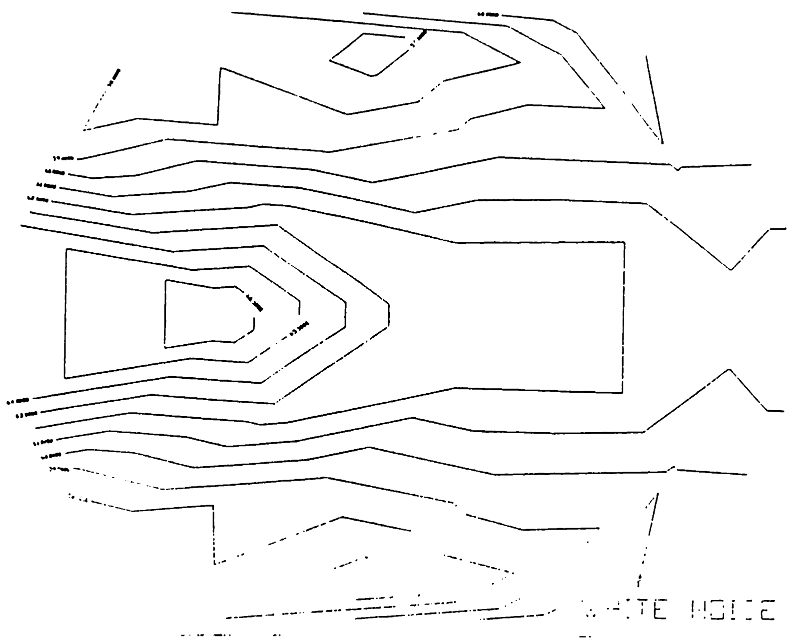


Figure 5.21. : Indication of the seats that receive the highest (green area) and the lowest (red area) sound pressure levels of 8000 Hz frequency sound

WHITE NOISE : Music is not a result of only one frequency of sound, but it is result of the mixture of different frequencies. For the interpretation and perception of music, it is necessary to provide successful distribution of all frequencies for all places in a concert hall. For this reason, to investigate the distribution of white noise is highly important for a concert hall, as the white noise is a sound formed by the mixture of all frequencies.

The distribution of white noise over the audience seating area of the Bilkent Concert Hall is given in Figure 5.22. There is a fairly uniform distribution with less sound pressure level variations between seats. The maximum value for the sound pressure level is about 66 dB and the minimum value is about 56 dB. A 10 dB difference is detected between the two extremes, which is a small variance in the concert hall.

The best places are seen as the middle seats of the first 4 or 5 rows, and the worst ones are again the seats closer to the side walls (Figure 5.23). The directionality of the sound source can again affect the distribution of sound intensity levels, and because of that reason, the seats located near the side walls at rows 'A' to 'D' may have higher values than it was measured. On the other hand, the seats closer to side walls, at the rows of 'E' to 'K' receive less sound pressure level than the rest of the seats in the room. For the white noise sound, the effect of reflected sound, in reinforcing the direct sound, is evident especially at the back rows, because the measured values at the back rows of the concert hall is closer to the values measured for the seats achieving highest sound pressure levels .



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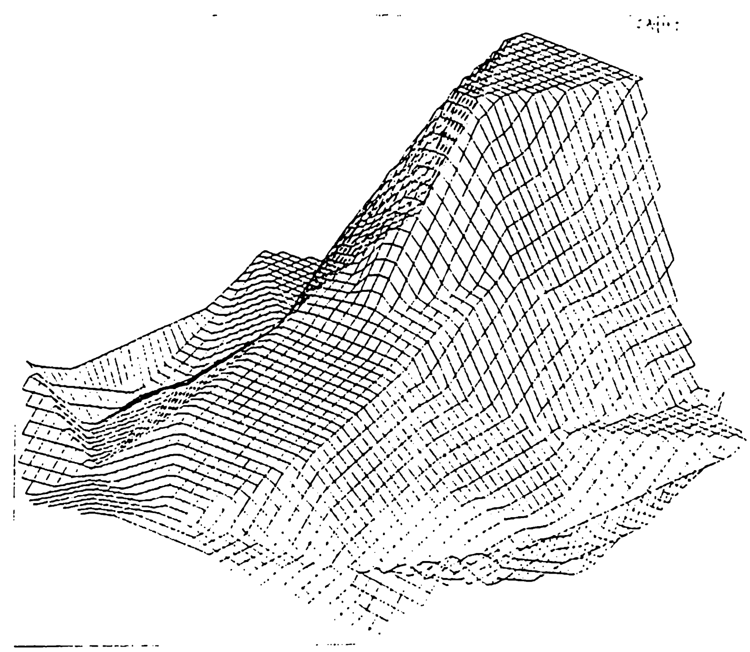

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Figure 5.22. : (a) Distribution of white noise over the audience seating area.
(b) Three dimensional presentation of the distribution of white noise in the hall

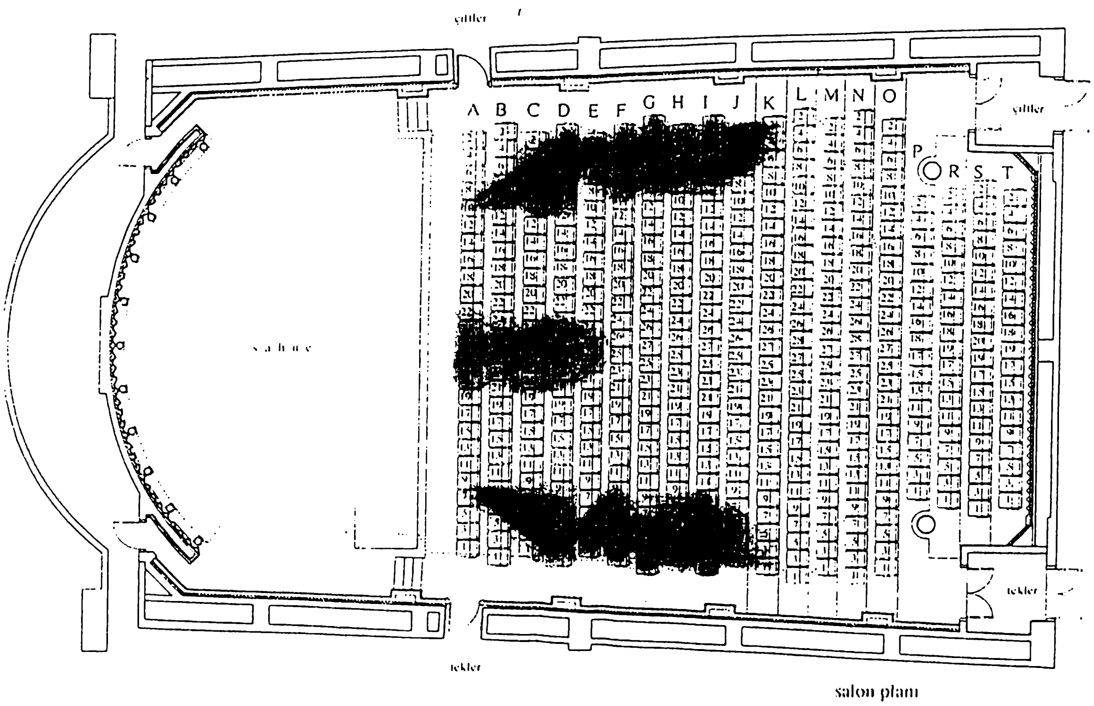

Figure 5.23. : Indication of the seats that receive the highest (green area) and the lowest (red area) sound pressure levels of white noise

5.3.2 EVALUATION OF THE DATA OF THE SECOND FLOOR

<u>63 HERTZ</u> : When the sound source generates 81.3 dB sound, the second floor of the concert hall receives 37 dB maximum and 31 dB minimum sound pressure levels. The results printed in Table 5.3 show that, the area designed for the chorus has received the signal most successfully than the other seats at the second floor. The first rows of the balcony area, and especially the seats located closer to the side walls at these rows, receive the least sound at the 63 Hz frequency sound. The rear wall of the main balcony reflects the sound back to the last rows of the space and reinforce the sound pressure level achieved there.

125 HERTZ : For this frequency range of sound, the data obtained is almost closer to the data analyzed for the main floor. The sound pressure level range varies from 36 dB to 52 dB at the main floor, and the variation is between 39 dB and 44 dB for the second floor. Most of the seats located at the second floor receive better levels of sound energy than the main floor. Again the seating area for chorus, and the last row of the second floor have the best values measured for the 125 Hz frequency sound.

250 HERTZ : The sound pressure levels obtained from the measurement of this frequency range is nearly equal for all seats. The maximum value is around 58 dB and the minimum value is around 61 dB. The distribution and reinforcement of sound are nearly equal over the second floor for all seats.

500 HERTZ : The same conditions analyzed for the 250 Hz frequency sound are seen for the distribution and reinforcement of 500 Hz frequency range. But this time, the last rows of the balcony and the chorus space receive less sound pressure levels than the seats located at other areas. The reason may be the absorption of sound energy by the rear walls of both areas.

1000 HERTZ : There are no great variations between the data measured at 1000 Hz frequency sound for the balcony floor, and the sound pressure level range is between 70 and 73 dB. The values obtained at the balcony floor are closer to the minimum values obtained at the main floor for this frequency range. The last row of the balcony receives the highest value, and the seats at the sides of row 'G' and 'H' receive the least sound energy at the second floor of the concert hall.

2000 HERTZ : The sound pressure level obtained at the main floor is between 68 and 84 dB, and at the balcony floor these values are between 67 and 72 dB. Although the minimum values achieved at both floors are equal to each other, there is a 12 dB difference between their maximums. The best seats are the ones located at the balcony side of the floor, and although the chorus is among the best seating locations for other frequencies, the values obtain do not suggest this situation for 2000 Hz frequency sound.

4000 HERTZ : The sound pressure levels, about 65 dB, obtained for this frequency range is nearly equal to the ones achieved for the minimum values at the main floor. This may suggest the loss of reinforcement of direct sound at 4000 Hz frequency range for the second floor. The seat placed in the middle of 'H' row ,(H-25), got the highest value during the measurements, and reinforcement of sound for this seat is clear at the balcony floor.

8000 HERTZ : The data obtained from the measurements show that, the loss of reinforcement of direct sound is the greatest at the balcony floor for the 8000 Hz frequency sound. Although the minimum value achieved at the main floor is around 50 dB, there are values, 46 dB, less than that value for the second floor. Again the seat located in the middle of the 'H' row receives the highest value of sound pressure level among the other seats at the balcony.

WHITE NOISE : The distribution pattern of white noise over the seating area at the second floor is very close to the distribution pattern achieved at the first floor. The seats located at the side aisles of the second floor receive sound energy less than the other seats. The seats located in the middle of the 'H' row, again, get the highest value during the measurements handled for the analysis of white noise at the second floor.

5.4 GENERAL EVALUATION OF THE CONCERT HALL

The study shows that the distribution of the sound pressure levels varies depending on the frequency ranges. Related with the frequencies, the boundaries of the hall sometimes reinforce the sound at a seat and sometimes do not. Because of that, one seat receiving high levels of sound for one frequency range may not have similar high value for the other frequency.

Music is not an event depending on a single frequency, but on the mixture of all the frequencies that it has been built up. The performance of a hall is affected by the distribution and reinforcement of all frequencies at every seat. For the Concert Hall of Bilkent, the best seating areas are nearly same for all frequencies studied, but the unsatisfactory areas of seating change depending on the frequencies generated.

A general evaluation of case study puts the following conclusions forward for the Bilkent Concert Hall:

1. The loss of low frequency sound is mostly seen at the back rows of the hall. The reason of this may not be the free field attenuation of sound depending on the

distance. There are some seats that receive more intense sound just next to these poor sound energy receiving areas at the same row. So a lack of reinforcement of low frequency sound at these areas is seen in the hall. The last two rows of the main floor of the Bilkent Concert Hall receive higher levels of sound pressure when compared with seats which are at the sides of K, L, M, and N rows. The reason is the back wall that reflects the sound back onto these seats, and this reflection reinforces the sound pressure level achieved by these seats.

The absence of low frequency sound in the space may cause the feeling of lack of warmth in the space. There are many instruments in the orchestra producing low frequency sound during the performances (Figure 5.24). When music is being performed in the hall, the audience seated in these poor locations, and receiving less bass sound, may complain about the music and claim the interpretation of the work is different than their expectations. On the other hand, the bass sound produced by a cello may satisfy another audience in another seat receiving the same interpretation of music.

For the Bilkent Concert Hall, there may be problems caused by the lack of low frequency sound produced by the instruments such as, cellos, bass viol, trombone, French horn, bass tuba, bass saxophone, etc. Also the placement of basses under the side balcony of the second floor may cause the loss of low frequency sound at the second floor of the concert hall.

The sound pressure level of low frequency sound is less at the balcony floor of the concert hall. The reason may be the flexible wood panels, which absorbs the low frequency sound of music. Especially, the reinforcement of the 63 Hz frequency sound is needed near the side walls of the second floor. Same problems described for the main floor are valid for the second floor, which may cause wrong feeling about the total acoustics of the hall.

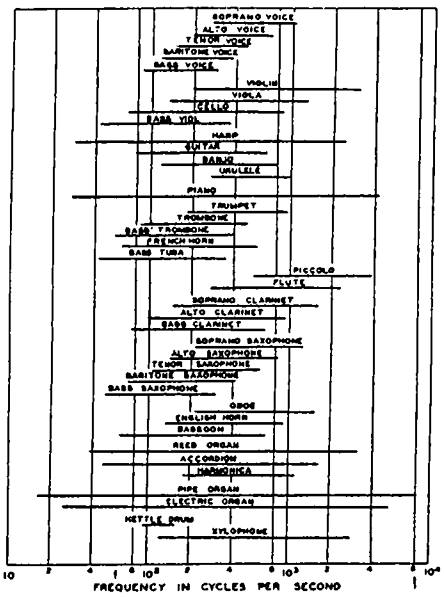

Figure 5.24. : Some instrument with the frequency ranges that they produce.(Olson, 1967)

2. The sound pressure levels studied for 500 Hz and 1000 Hz frequency sound are almost equal for all seats in the concert hall. There are no great variations of sound energy measured at different seats for these frequencies. It can be said that there is a good reinforcement of direct sound for all areas in the concert hall. Because of this evenly distribution of sound, there will be no difference in perception of same music, at different seats for the middle frequency sound.

The surfaces reflect the sound waves back to the space and this increase the level of sound for 500 Hz and 1000 Hz frequency sound. The sound pressure levels measured at the seats of the second floor of the space is also closer to the ones at the main floor. This indicates a total success of the boundaries of the concert hall, in reinforcing especially the 500 Hz frequency sound , and in distributing it equally in the space.

3. The sound pressure levels measured for the frequencies increase gradually beginning from 63 Hz up to 2000 Hz. After the 2000 Hz frequency sound, a drop is seen in the sound pressure levels measured for 4000Hz and 8000 Hz frequency sounds. Same results were also achieved during the measurements done just in front of the sound source. Because of that reason, variations on the sound pressure levels may also depend on the instruments used besides the treatment of the sound by the concert hall.

4. The most unsatisfactory results were found for the 2000, 4000, and 8000 Hz frequency sounds. The reinforcement of sound at these frequency ranges are not even within the hall, and the sound pressure levels measured at these frequencies show variations at different locations of the hall.

Sound energy at high frequencies and their decay in the concert hall are the factors affecting the brilliance in the space. When there is attenuation of high frequency sound with variations in the space, the perception of the total music being performed shows variations within the same space at different locations. In the Bilkent Concert Hall, at the seats indicated in red at Figures 5.17, 5.19, and 5.21 problems may arise in the perception of high frequency music performed by instruments like violin, piano, piccolo, etc.

On the second floor of the concert hall of Bilkent, there is a great drop seen in the measured values for the sound pressure levels of 4000 Hz and 8000 Hz sound when compared with the results achieved at the main floor. To eliminate perceptual differences of music between the two floors, reinforcement of 4000 Hz and 8000 Hz sound must be introduced for the seating areas located at the balcony floor of the Bilkent Concert Hall.

5. Although there are only a few instruments (electric and pipe organ) producing sound over 4000 Hz (Figure 5.24), it is important to provide best conditions for the existence of these frequencies in the space. In the Bilkent Concert Hall, only the first two or three seats at the sides of rows from 'H' to 'O' seem to have problems for the high frequency sound of 8000 Hz.

6. The white noise distribution in the concert hall is more satisfactory than the single frequency ranges. The reinforcement of direct white noise is pleasing at the rear of the room, which is an important feature for the total acoustical quality of the concert hall.

7. The areas that receive less sound pressure levels are mostly the ones closer to the side walls. The reason for this can be the balcony floor which reduces the sound coming downwards after being reflected from the ceiling. As there are no horizontal surfaces cutting the reflected sound coming down on the areas in the middle of the hall, the seats placed at these locations receive higher intensity levels of sound than the remaining parts of the concert hall.

8. The positions of the movable wooden panels, placed on the walls of the concert hall, were not changed during the study. In the present situation, as the angle between these panels are kept the same all along the surfaces, the present wall pattern adds unequal amounts of reinforcement to all the areas in the hall. The necessary reinforcement of sound may be achieved at some locations by changing the angle of some of the panels. The panels may reinforce the perceived level of sound pressure if they are positioned to reflect sound towards the seats where the received sound level is weaker compared to the other parts of the hall.

9. Referring to Figure 2.6, it is seen that the central frequency of speech is around 1000 Hz. Bilkent Concert Hall gives highest measured values of sound pressure levels at the frequencies of 500 Hz , 1000 Hz, and 2000 Hz, and less variation between the measured sound pressure levels are reported for the frequencies at 500 and 1000 Hz sound. Depending on these results it may be suggested that the hall is very suitable and may be used for conference activities too, although it was designed for musical performances.

10. In the beginning of this chapter it was stated that the measurements were done at night. The reason for this was the excessive level of background noise caused by the students exercising in the rehearsal rooms on both sides of the concert hall. The background noise was measured between 38 and 45 dB while the building was occupied with the students in the day time. The measured background noise level was found between 18 and 24 dB at night. Although the walls of the hall seem to be designed and constructed well, the passage of the sound from outside can not be completely avoided. This may be caused by the single side wall doors opening directly to the space. Therefore, substitution of these doors with double ones is suggested to reduce this sound transmission.

11. For all the frequencies studied, the sound pressure level measured just in front of the source showed great differences with the sound pressure levels measured at the first rows of the concert hall. The reason may be the behavior of sound in the near field of the source. As mentioned before in section 2.3 , sound pressure level can show variations, and sound particles may not be in the direction of propagation within the near field of the sound source.

12. The stage of the Bilkent Concert Hall has a width of nearly13 meters and a depth of 9 meters. These dimensions are rather small when compared to the ones suggested by Beranek (18 ×12 meters)(Music 489) and by Lord and Templeton (12.2 × 12.2) (68).

Although using risers on the stage provides comfortable conditions during the performance, it is not seem possible to apply this design solution for the stage of the Bilkent Concert Hall as it has limited dimensions, especially in depth.

6. CONCLUSION

The purpose of this study has been to describe the important factors to be considered in the design of concert halls for symphonic music, and to investigate optimum acoustical conditions which can be achieved with the passive sound control techniques.

A concert hall must meet the needs of performers, and satisfy the expectations of audience. Both aesthetic, and scientific approaches must be involved in the design for the full enjoyment of music in the space. The same attention must be paid from the smallest detail to the surface treatment of the interiors, to the design of the size, shape, and volume of a concert hall.

For music, it is very difficult to state standards for good listening conditions as aesthetic and emotional judgments are involved. Also it is difficult to define and measure as some of the criteria are totally subjective. Therefore, it is suggested that the design of rooms for music to be handled as an art as much as a science.

Because of their wavelength characteristics, frequency components of a musical sound behaves separately, and different than each other when they are incident on the same surface at the same time. This has been shown in the experimental section of the thesis. The Bilkent Concert Hall in Ankara was chosen for the analysis of the musical sound in an enclosed space, and the results of the study show that, the hall is sometimes successful acoustically and sometimes not, depending on the prevailing frequency range of the sound source. It was found out that, every frequency component of music behaved differently in the concert hall. From the results of the case study, some changes have been found necessary in order to achieve closer sound pressure levels in all seats for all frequencies.

Although the acoustics of concert halls are usually designed as a result of elaborate calculations, nearly always the improvement of the obtained acoustical environment becomes necessary with the installation of reflective or absorptive surfaces after the construction. The installation of these surfaces to ameliorate the acoustics of the concert hall of Bilkent, however, has not been suggested as there is no equipment available at this time to verify their effect on the improvement of the prevailing acoustical situation.

Limited facilities were available during the study for the evaluation of the Bilkent Concert Hall. Only a sound level meter and its octave band filter were available, and the necessary noise generator was obtained from the Ministry of Public Works. If it were possible to use a 'Building Acoustic Analyzer', there could be chance to measure the reverberation time, sound absorption, reflection, distribution, insulation, speech intelligibility which are important objective criteria in the acoustical design of spaces for music. Also, the acoustical changes, and improvements in the hall, with the introduction of the new acoustical environment (e.g. created by changing the angles of the movable wooden panels) could have been recorded with the help of building acoustic analyzer. Because of this limitation in available facilities, no distinct design proposals to improve the acoustics of the Bilkent Concert Hall have been suggested.

It is hoped that, the available knowledge summarized in the thesis on the nature of musical sound, its behavior in enclosed spaces, the subjective and objective criteria necessary for the successful presentation of music, the importance of size, volume, and form in the design of concert hall, and the role of ceiling, wall, and floor surfaces in acoustics of the concert hall, both for the orchestra and for the audience, will be a guide to the acoustical planning of the future concert halls. It is also expected the findings of this study will be used in the amelioration of the Bilkent Concert Hall and in the design of new concert halls, and remodeling of the old ones.

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APPENDIX

Glossary:

Absorption: The ability of a material to intercept the propagated sound waves in and change them into heat energy.

Acoustics: (1) The science of sound, dealing with the control, production, transmission, reception and effects of sound waves. (2) The qualities that determine the ability of an enclosure to reflect sound waves in such a way as to produce distinct hearing.

Balance: Equal perception of music from all places on left and right sides of the hall.

Blend: It is the harmonious mixing of sounds from various instruments in the orchestra.

Boomy (in music): Having an excessive emphasis on the tones of lower pitch in reproduces sound.

Brilliance: Brilliance is the property of sound being bright, clear, ringing, and rich in harmonics.

Brittle: Brittle sound in music is the sound without bass component. Lack of warmth in music causes brittle sound in space.

Complex Tone: A sound sensation characterized by more than one pitch.

Creep: The reflection of sound along a curved surface.

Decibel (dB): Decibel is a unit for expressing the relative intensity of sounds on a scale from zero for the threshold of hearing to about 130 for the threshold of pain value. It is a logarithmic scale of a particular sound pressure level depending on a standard reference value.

Definition (or clarity) : When the sound is clear and distinct in the space, a hall is said to have definition.

Diffraction: Ability of a sound to pass around a screen or a barrier. Lower frequency sounds can diffract around objects more easily because of their long wavelength.

Diffusion: An even dispersion of sound after incident on a surface in a room, with no directionality of sound waves.

Dynamic range : The range of sound levels over which music is heard. It extends from the faintest level (noise of the audience) to the loudest level produced by the performers.

Early Decay Time: Early decay time is a measure of the sound decay measured either over the first 10 dB part of the decay process, or over a fixed interval of 160 msec.

Echo: Echo is the delayed reflection loud enough to be perceived as a separate sound which disturbs the listener.

Ensemble: It is the musicians ability to play in unity and ease of hearing among performers.

Flutter Echo: It is a rapid succession of reflected sound waves resulting from a single initial sound pulse.

Formant: The loudest harmonic in the frequency spectrum of the instruments, that does not change with the fundamental frequency.

Freedom from echoes: Elimination of delayed reflections (echoes) from the space.

Freedom from noise: The isolation of all external or internal unwanted sound in the hall.

Frequency: The number of cycles per second that a vibrating system completes. Units are c/s, or more commonly Hertz.

Fundamental Tone: The component tone of the lowest pitch in a complex tone.

Fundamental Frequency: The frequency component of the lowest frequency in a complex sound.

Harmonic: A harmonic is a partial whose frequency is an integral multiple of the fundamental frequency.

Immediacy of response: This criterion is the hall's ability to give the musicians the feeling of immediate response when a note is being played.

Initial Time Delay Gap: Initial time delay gap is the time difference between the sound that arrives directly to the ear and the first reflection which arrives from walls or ceiling.

Intimacy (or presence) : The feeling of being enclosed in a space with the sound field enveloping the listener is important while designing the space for music.

Liveness: Subjective impression of reverberation time.

Loudness: The subjective judgment by an individual which tends to be influenced by sound pressure and frequency.

Loudness Level: The loudness level in phones of a noise is defined as the sound pressure level in decibels of a 1000 Hz tone which sounds equal in loudness to the sound which is being rated.

Noise: Any sound that is unwanted or interferes with one's hearing of something.

Note: The conventional sign used to indicate the pitch or duration or both of a tone sensation.

Pitch: The property of a sound and especially a musical tone that is determined by the frequency of the waves producing it.

Pure Tone: The simplest kind of sound which is entirely composed of sound waves of a single frequency.

Reflection: Sound energy returned after hitting on a surface, rather than being absorbed as heat energy within the surface.

Reverberation: The continuation, built up of sound in an enclosed space, because of multiple reflection from surrounding enclosing walls, floors and ceiling, after the sound source has been stopped.

Reverberation Time: It is the time taken for a sound intensity to decay by 60 dB after the sound source is switched off.

Sound: The sensation perceived by the sense of hearing which results from rapid variations in air pressure.

Sound Intensity: It is the power radiated in a specified direction through unit area normal to this direction.

Sound Power (W): It describes the energy of sound source.

Sound Pressure: It is the variation from normal atmospheric pressure caused by the flow of sound energy as a motion of molecules in the air.

Sound Waves: Sound waves are longitudinal pressure waves usually propagated through the air but also through solid and liquid materials.

Tempo: Term used in musical terminology as meaning the rate of movement or speed.

Texture: Texture is the impression created in the mind of listener by the sequential arrival of reflections after the direct sound

Timbre (or quality): It is a characteristic property of music that enables the listener to recognize the kind of musical instrument which produces the tone.

Tone: A tone is a sound sensation having pitch or a sound wave capable of exciting an auditory sensation having pitch.

Tonal quality : Tonal quality of a music hall can be expressed by its ability of not distorting the sound produced by the performers.

Uniformity : Having an unvaried quality or state of music for every location within the whole space.

Warmth: Warmyh in music is defined as liveness of bass, or fullness of bass tone relative to that of mid frequency tone

Wavelength (λ): The distance that the sound travels in one cycle.

White Noise : It is a sound with a balanced mixture of frequencies over a wýde range.